The Voyage of Mariner 10

National Aeronautics and
Space Administration

NASA SP-424

The Voyage of Mariner 10

Mission to Venus and Mercury

James A. Dunne and Eric Burgess

Prepared by
Jet Propulsion Laboratory
California Institute of Technology

NASA Scientific and Technical Information Office 1978
National Aeronautics and Space Administration
Washington, DC

Library of Congress Cataloging in Publication Data

Dunne, James A.
The voyage of Mariner 10.

(NASA SP ; 424)
Bibliography: p. 221
Includes index.
1. Venus (Planet)–Observations. 2. Mercury (Planet)–Observations. 3. Project Mariner. I. Burgess, Eric, joint author. II. California Institute of Technology, Pasadena. Jet Propulsion Laboratory. III. Title. IV. Series: United States. National Aeronautics and Space Administration. NASA SP ; 424.
QB621.D86 523.4'2 77-18956

For sale by the Superintendent of Documents
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Stock No. 033-000-00710-8

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Foreword

THE MISSION OF MARINER 10 was unique in several ways. It was the first American spacecraft to take photographs of Venus. It was the first to use the gravity and motion of one planet to alter the flight path of a spacecraft and send it to another planet. It was the first to explore the planet Mercury, which was previously but a hazy image in the best Earth-based telescope pictures.

The success of Mariner 10 in attaining—and exceeding—its goals is attributable to the dedicated effort of the relatively small but exceedingly competent and highly motivated group of men and women from universities, industry, and government who made up the Mariner Venus/Mercury 1973 project team.

Mariner 10 visited Venus once and Mercury three times in a period of a little over 500 days on a voyage of more than a billion kilometers. Shortly after the spacecraft left Earth it was oriented to the Earth and the Moon and returned the first of over 8000 pictures that were taken throughout its trip. These pictures of the Earth and Moon provided a calibration for later pictures of Venus and Mercury.

During the cruise from Earth to Venus, Mariner 10 acquired data about the environment of interplanetary space and obtained information about the comet Kohoutek, which passed by the Sun shortly after the launch.

On February 5, 1974, after traveling 236 million kilometers, Mariner 10 skimmed past Venus within 12 kilometers of the preplanned aim point. Over 3500 pictures were obtained as the spacecraft first saw a thin crescent and then the full face of Venus. These photos revealed a global distribution of ultraviolet clouds which rotate about the planet some 50 times faster than the planet rotates on its axis.

On March 29, 1974, following several additional course corrections which were made after leaving Venus, the spacecraft reached its primary goal: Mercury. Man obtained for the first time brilliantly clear pictures of this planet.

Mercury looks a great deal like the Moon. However, it has a dense interior and unexpectedly possesses a weak magnetic field. Mariner's cameras also revealed surface features not previously seen on other planets.

The surface of Mercury records the early history of the cataclysmic events that occurred during the formation of our solar system. The primordial state of the planet's surface, when studied in combination with similar data obtained from the Moon and Mars, should provide a great step forward in our understanding of the origin and evolution of the solar system and thus of our planet Earth.

Even though the spacecraft experienced several serious problems during its trip to Mercury, and its gas supply nearly ran out, it performed its basic job flawlessly, and plans were laid for a return visit to Mercury about 6 months later.

Through the efforts of an ingenious and dedicated operations team the art of "solar sailing" was perfected and the spacecraft's gas usage was greatly reduced, thus permitting not one but two returns to Mercury. These bonus revisits provided additional pictures of Mercury's surface, including a spectacular view of the planet's south pole. The third encounter unequivocally confirmed the existence of Mercury's magnetic field.

This book records the historical details of the Mariner 10 mission from its original concept to its ultimate success. It provides a selection of some of the images obtained by the spacecraft at both Venus and Mercury. A detailed Atlas of the Mercury images is being published separately by NASA.

Mariner 10 reaped a bountiful harvest of new information about the inner planets of the solar system, information which combined with that from the exploration of other planets may provide us with an increasingly clear view of the origin of our solar system and possibly a clue to its destiny.

John E. Naugle
Chief Scientist
National Aeronautics and Space Administration

Introduction

RARELY IN THE LIFETIME of an individual is he privileged to witness and be part of an historic first for mankind. Such has been my privilege. Even more rarely is one privileged to be part of such a dedicated, competent, and professional group as comprised the Mariner Venus/Mercury Project Team. It was a moderately small group of diverse talents, dedicated to accomplishing an historic scientific voyage to Mercury by way of Venus, and to do it within tight schedule and cost constraints.

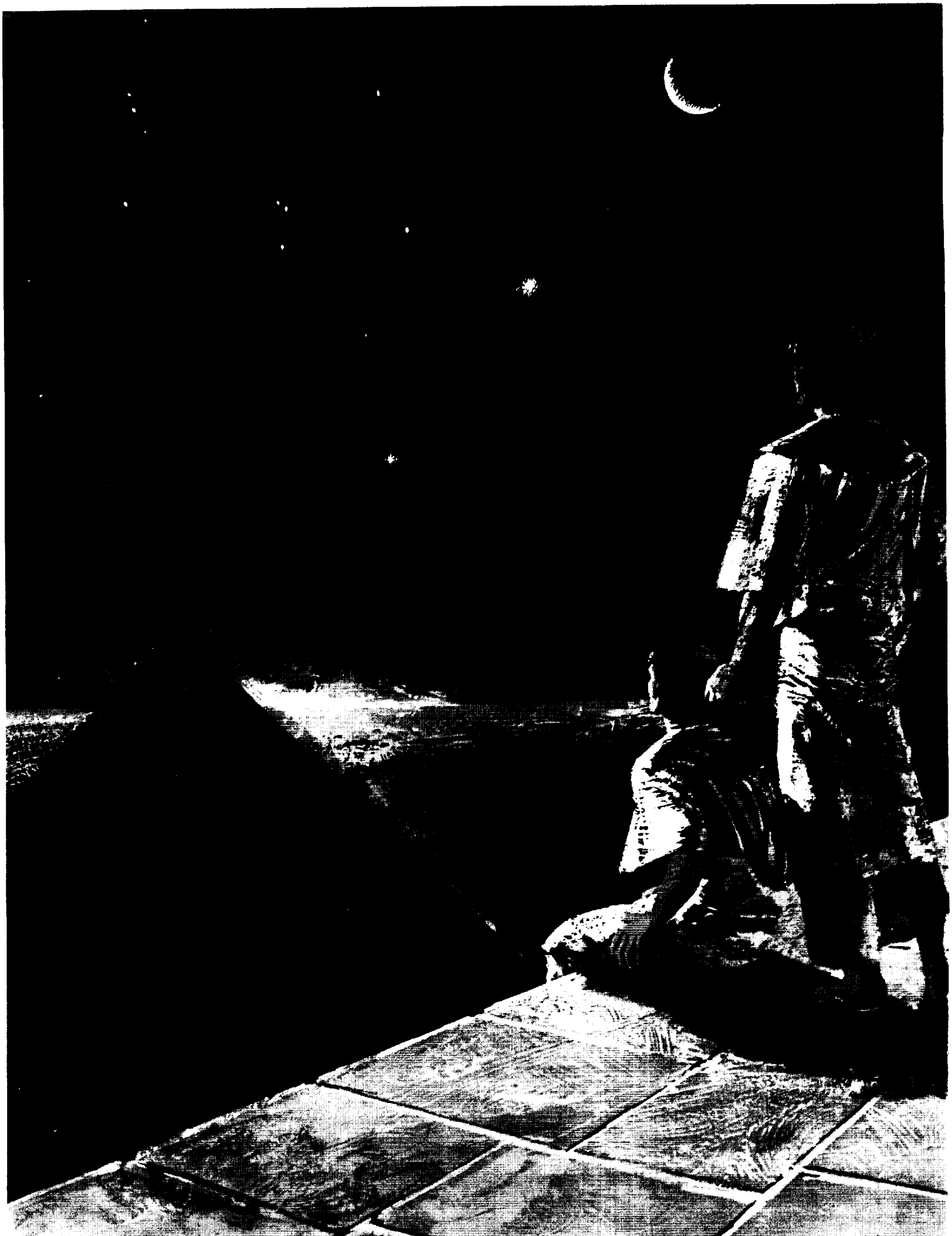
These people met and exceeded the challenges and further distinguished themselves several times during the flight of Mariner 10 when emergencies were encountered which threatened the success of the mission. Their professional response to these emergencies proved the competence of this truly remarkable team of NASA, Boeing, Philco-Ford, Planning Research Corporation, university, and Jet Propulsion Laboratory people. Without this team the exciting discoveries made on the Mariner 10 flight to Venus and Mercury would not have been possible.

W. Eugene Giberson
Mariner Venus/Mercury Project Manager
Jet Propulsion Laboratory

Acknowledgment

THE AUTHORS ARE GRATEFUL for comments and suggestions from many persons connected with this historic voyage to the innermost planet. Many scientists and project staff members provided material during interviews which were part of the research for this book. Of particular importance were valuable initial suggestions or later comments on all or parts of the several drafts by H. S. Bridge, A. L. Broadfoot, V. C. Clarke, Jr., N. W. Cunningham, G. E. Danielson, Jr., R. Dod, J. Eraker, W. E. Giberson, H. T. Howard, B. C. Murray, N. F. Ness, W. Purdie, J. A. Simpson, R. G. Strom, and J. N. Wilson.

Personnel from the Jet Propulsion Laboratory's Mariner Venus/Mercury Project staff, Public Information Office, Technical Information and Documentation Division, and others were particularly helpful in providing information, arranging interviews, and producing the book. Members of the teams associated with TV imaging and processing the pictures, including Nancy Evans and James M. Soha, must receive special thanks for providing many illustrations of Venus and Mercury included herein.



Chapter 1

Earth's Sister and the Twilight Planet

THE INNER PLANETS Mercury and Venus, orbiting the Sun within Earth's path around the central luminary of the Solar System, have been known from ancient times. Early man thought that there were four of these wandering stars, attendants to the Sun—two in the morning skies and two others in the evening skies.

Ancient Greeks were familiar with the dull-white star that shone steadily across the clear skies of the Aegean Sea in the warm glow of dawn. They called it Apollo. In Egypt the horoscopus priests of Thebes looked across the Nile toward Karnak and recognized it as the evil star of Set fleeing upward before Amun-Ra at dawn to be vanquished and disappear in the brilliance of the rising sun god.

Both Greeks and Egyptians thought the morning star different from another star seen close to the Sun after sunset. The Greeks named the evening star that lingered in the sunset glow across the Ionian Sea Hermes, the winged messenger of the gods, while the Thebans recognized it as Horus, the vanquisher of Set and follower of Amun-Ra.

By about 350 B.C., the time of Plato, the Greeks acknowledged the morning and evening stars as being one planet. The modern name, Mercury, is the Roman name for Hermes, the messenger of the gods. The Greek Hermes is still used as the adjective Hermian—of or relating to Mercury. Similarly, ancient astronomers did not recognize Venus as one planet. When east of the Sun and seen in the western sky after sunset, the planet was called Hesperus. When west of the Sun and rising before it, the planet was called Phosphorous. About the 12th century B.C., Homer mentions Venus but considers it as two objects. Pythagoras is said to have recognized the single identity of Phosphorous and Hesperus about 500 B.C.

The confusion between the morning and evening stars is reflected even as late as the writings of Eudoxus about 400 B.C., probably the earliest Greek astronomer, who is believed to have derived his knowledge of the planetary movements from Egypt. Although he stated the periodic times of the planets Mars, Jupiter, and Saturn quite accurately, he was much in error with times for Mercury and Venus. This contrasted greatly with his statements about the synodic periods: that is, the times between the reappearances of planets in the same configuration in Earth's sky. His synodic periods were quite accurate for Venus and Mercury as well as for the outer planets. Thus he showed accurate knowledge of the times when the evening and morning stars would appear, but seemed ignorant of their true motions around the Sun.

Planets of the Solar System (Fig. 1-1) are today known to consist of three distinct types: small, dense, inner planets with solid surfaces (Mercury, Venus, Earth, Moon, and Mars), large, predominantly gaseous, outer planets (Jupiter and Saturn), and large, ice-giant, outer planets (Uranus and Neptune). Additionally there is a small, outermost planet, Pluto, large and small planetary satellites of various types, a group of minor planets concentrated between the orbits of Mars and Jupiter, many comets, meteor streams, and general debris.

Mercury is the innermost planet of the Solar System; Venus orbits the Sun between the orbits of Earth and Mercury. Both planets not only were confusing to the ancients but continued to confuse modern astronomers, although in other ways. For many years the rotation periods of these planets on their axes were unknown, and neither planet revealed any definite surface markings, even to the best of Earth-based telescopes.

Mercury's surface could not be observed because of the planet's small size, its distance from the Earth, and closeness to the Sun, while Venus was shrouded in mystery because of a dense atmosphere with thick clouds that only showed markings in photographs taken by ultraviolet light.

Mercury's distance from the Sun averages 58 million kilometers (36 million miles), which is about 38 percent of Earth's distance, while Venus, at 108 million kilometers (67 million miles), is about 72 percent of Earth's distance from the Sun.

Since the planet Mercury is so close to the Sun and moves along its orbit 1.5 to 2 times faster than Earth, it flits from side to side of the Sun so as to be seen only just before sunrise or just after sunset. Its mothlike rapid motion and brief appearances and disappearances are probably why the ancients associated it with the wing-footed messenger of mythology. By contrast, Venus comes closer to Earth, moves farther from the Sun in the evening and morning skies, appears placid and brilliant, and is perhaps the most beautiful object in the skies. "Mistress of the Heavens" said the Babylonians, while the Romans associated the planet with the goddess of beauty, Venus.

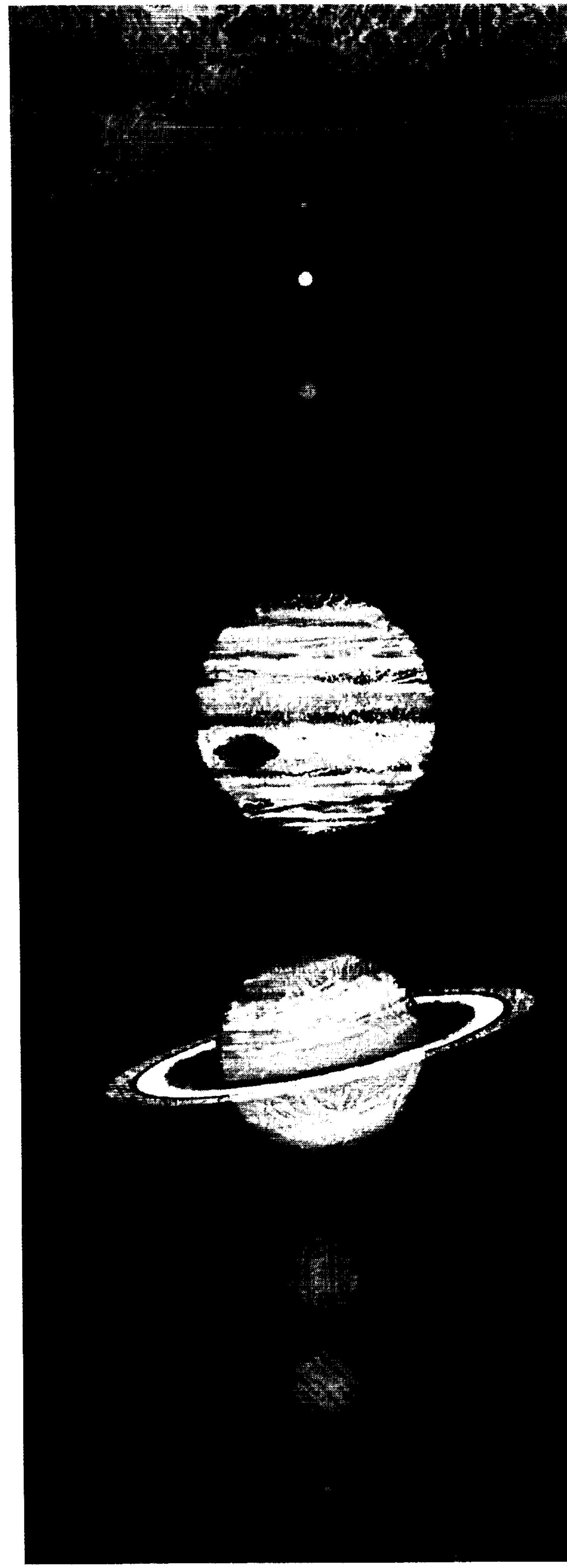


Fig. 1-1. The inner, or terrestrial-type planets of the Solar System are quite small bodies relative to the outer giants. Yet these inner planets are the ones possessing solid surfaces which permit exploration.

Apparitions of Inner Planets

It is instructive to look at the inner planets Mercury and Venus from the standpoint of the earlier astronomers. At the beginning of recorded history men watched the motions of the planets against the background of stars, but it was many centuries before they deduced that the planets, including the Earth, move around the Sun in almost circular orbits. This awareness was slow in acceptance because early philosophers, later backed by the Christian Church, accepted an Earth-centered dogma. It was not until after the invention of the telescope in the early 1600's that the dogma was dispelled and a Sun-centered Solar System was accepted generally.

Galileo first discovered that Venus exhibits phases like the Moon. Cautiously he laid claim to his discovery in an anagram, published in 1610, which translated into English reads: "The mother of the loves (Venus) emulates the phases of Cynthia (the Moon)." Galileo used this observation of the phases of Venus as a strong argument for the truth of the Copernican theory that the Solar System is centered on the Sun, not the Earth.

Because Mercury and Venus orbit the Sun within Earth's orbit, they are termed inferior planets. As seen from the Earth, inferior planets appear to move close to the ecliptic (the apparent yearly path of the Sun relative to the star sphere, which is also the plane of the Earth's orbit projected against the stars), and to move backward and forward, oscillating to either side of the Sun and never far from it in the sky. The maximum angular distance to east or west of the Sun is termed elongation. At eastern elongation, Mercury and Venus are seen in the evening sky as evening stars because they appear to follow the Sun in its daily motion across Earth's sky owing to the rotation of the Earth (Fig. 1-2). At western elongation, they are ahead of the Sun and are seen as morning stars before sunrise.

Because the orbits of these inferior planets are completely contained within the Earth's orbit, both Mercury and Venus periodically pass between Earth and Sun. This is termed inferior conjunction (Fig. 1-3). At other times, when the planets are on the far side of the Sun from Earth, they pass through superior conjunction. Because the orbits of the Earth and the two planets are not exactly in the same plane—they are tilted slightly with respect to each other like crossed hoops—Mercury and Venus normally pass through conjunction above or below the Sun. Infrequently, the orbits line up so that the planets cross the face of the Sun in a transit or behind the

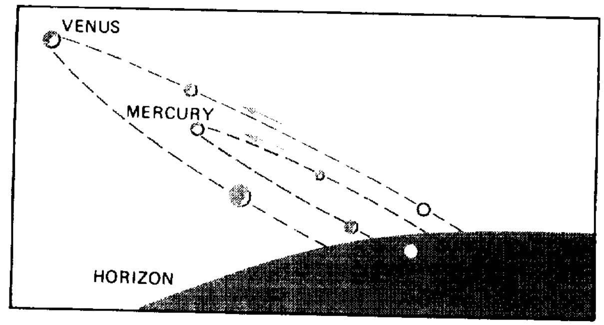


Fig. 1-2. Because Mercury and Venus orbit the Sun within Earth's orbit, they stay close to the Sun in the sky as seen from Earth. At their greatest angular distance from the Sun they are said to be at elongation. Here the two planets are shown at eastern elongation; they set after the Sun and appear as evening stars.

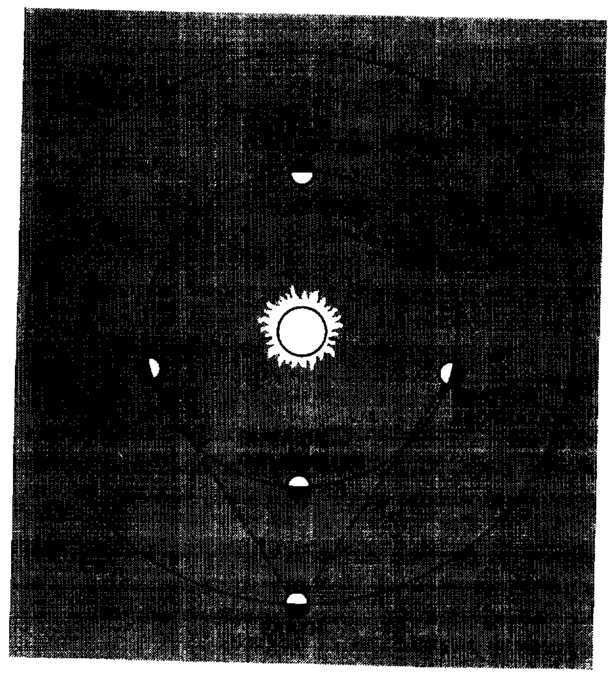


Fig. 1-3. When inner planets are between Earth and Sun they are said to be at inferior conjunction. When on the far side of the Sun they are at superior conjunction. Sometimes at inferior conjunction the planes of the orbits align, and Mercury and Venus are seen as dark dots on the face of the Sun as they pass in transit.

Sun in an occultation. Occultations are not observable because of the brilliance of the Sun, but transits are.

Transits of Venus take place very rarely: the most recent occurred in 1882; the next are not due until the beginning of the next century–June 7, 2004, and June 5, 2012 (they occur in close pairs). The first recorded transit of Venus across the face of the Sun was observed by Jeremiah Horrocks and William Crabtree in Manchester, England, on December 4, 1639. In 1769, a search for a place from which to observe one of the next pair of transits of Venus led Captain Cook to visit the newly discovered Tahitian Islands and later to discover New Zealand.

Transits of Mercury occur much more frequently. The first recorded observation was by the philosopher critic Pierre Gassendi, at Aix, France, on November 7, 1631. The most recent was visible from the East Coast of the United States on November 11, 1973. The next transit will take place on November 12, 1986.

Mercury revolves around the Sun in a period of 88 days; Venus in a period of 225 days. But their visibility in Earth's skies depends also upon Earth's movement around the Sun. So Venus repeats its apparitions (elongations and conjunctions) in a synodic period of approximately 584 days. This period was known to within 14 days by the ancient Egyptians. Mercury repeats approximately every 116 days. The ancient Egyptians were even closer to this period–they recorded it as 110 days. Since Mercury's orbit varies much more from a true circle than does that of Venus, or Earth, the repetition of Mercury's positions relative to the Sun in Earth's skies varies too. The angular distance of Mercury from the Sun in the sky at elongation also varies, from only 18 degrees to as much as 27 degrees.

Mercury is intrinsically a relatively dark object. Like the Moon it does not reflect much of the sunlight falling upon it–it is said to have a low albedo–so it does not appear very bright in the sky. Moreover, Mercury can rise before or set after the Sun by only 2.5 hours at the maximum, so it is rarely seen in the dark sky, but usually only in the twilight glow. Because of its rapid orbital motion the planet cannot be seen for much longer than two weeks around the time of each elongation. The average interval between Mercury's appearance as an evening and a morning star is 44 days.

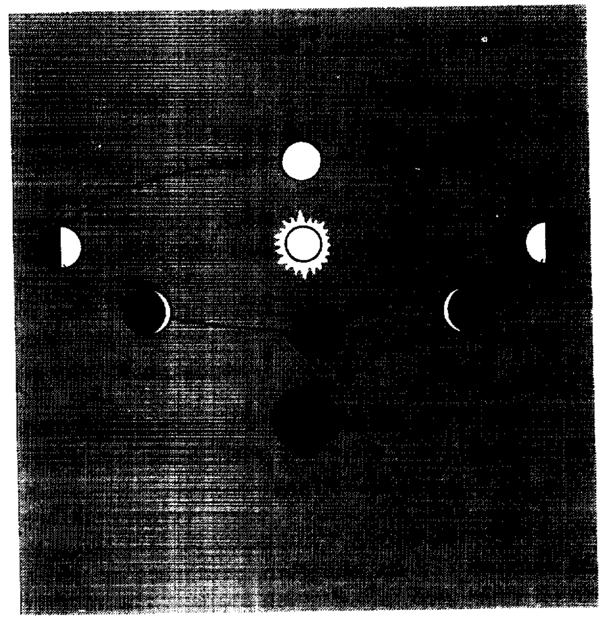


Fig. 1-4. Galileo discovered that Venus, seen through a telescope, shows phases like those of the Moon.

By contrast, Venus moves as much as 47 degrees from the Sun, so that it is seen in the late evening or early morning skies as the brightest starlike object. Because Venus reflects a large proportion of the Sun's light falling upon it–it has a high albedo–the planet appears very bright in the skies of Earth. When at its brightest, about one month before and after inferior conjunction, Venus casts distinct shadows. At this time a telescope shows it as a fat crescent shape.

Venus can be observed for many months at each elongation; it has even been seen through binoculars as it passes above or below the Sun at closest approach. It is also clearly visible in daylight if an observer knows where to look. For example, when Venus appears close to the Moon in the sky, the Moon can be used as a guide to finding the planet. Venus passes from greatest elongation as an evening star to greatest western elongation as a morning star in about 140 days, and from morning star back to an evening star in about 430 days.

As the inferior planets move around the Sun, their phases as seen from Earth (Fig. 1-4) are comparable to those of the Moon. When Mercury and Venus are on the far side of the Sun from Earth, they appear fully illuminated like a full moon, but because of their great distance then, they are unfavorably placed for observation and show relatively small discs. At eastern and western elongations, the two planets appear about half illuminated. Then as they move between Earth and Sun, Venus and Mercury display a narrowing crescent phase to Earth-based observers until, if they cross the disc of the Sun, they appear as black spots upon it. Most times they pass either above or below the solar disc and thus, in a telescope, they can be seen as a very fine crescent all the way through inferior conjunction.

Fig. 1-5. Craters on terrestrial planets and satellites, like these revealed by a Mariner spacecraft on a satellite of Mars, are thought to be the evidence of the final stages of an accretion process that took place some 4.5 billion years ago.

The Questions

Planets of the Solar System probably formed four to five billion years ago when hosts of small rocky particles and clouds of gases collected together by their own gravity. Gravity is a universal property of matter, as a result of which every particle, irrespective of size, attracts every other. Thus, left to themselves in space, individual particles tend to collect together into larger masses.

After the Sun condensed from the primordial nebula, planets of different sizes and probably different compositions accreted from concentrations of matter present at various distances from the Sun. Evidence for this process of accretion is presented in the cratered surfaces of planetary bodies ranging from small satellites such as Deimos and Phobos (Fig. 1-5) to planets such as Mars. These craters are believed to have been produced by falling bodies some time after the main stage of planetary formation.

The major differences among the terrestrial planets may have arisen because these planets formed at different distances from the Sun and thus consisted of different materials from the beginning. For example, Mercury might have formed from materials rich in iron, whereas Venus formed from silicate-rich materials. Earth may have accreted in a region of the primordial nebula where there were water-containing materials, while Venus did not.

Scientific information about conditions on other planets is important to increased understanding of the evolution of the Solar System and therefore our own planet Earth. Each spacecraft visiting a distant planet for flyby or landing adds more to this basic store of human knowledge. A number of spacecraft had already visited Venus; two successful flybys had been made by Mariners, and five Soviet Venera spacecraft had flown by, orbited or landed capsules on the surface. From these missions, combined with many decades of Earth-based observations using visible, ultraviolet, microwave, and spectroscopic techniques, Venus was known to possess a high surface temperature of around 475°C (887°F) and a pressure at the base of the massive atmosphere about equal to that at a depth of 400 fathoms in the Earth's oceans. Venus was revealed as a hot, dry planet with only traces of water vapor in its predominantly (95%) carbon dioxide atmosphere. Spectroscopic studies had indicated the presence of sulfuric acid droplets high in Venus's atmosphere, which had been shown to possess distinct layering, both above and below the light-obscuring visible clouds.

Venus, virtually Earth's twin in diameter—12,104 km (7521 mi) vs 12, 657 km (7926 mi)—in mass, and in density, is distinctive from its nearest planetary neighbor, Earth, in terms of its atmospheric composition and slow, retrograde spin. How these differences arose remains a central question in planetary science.

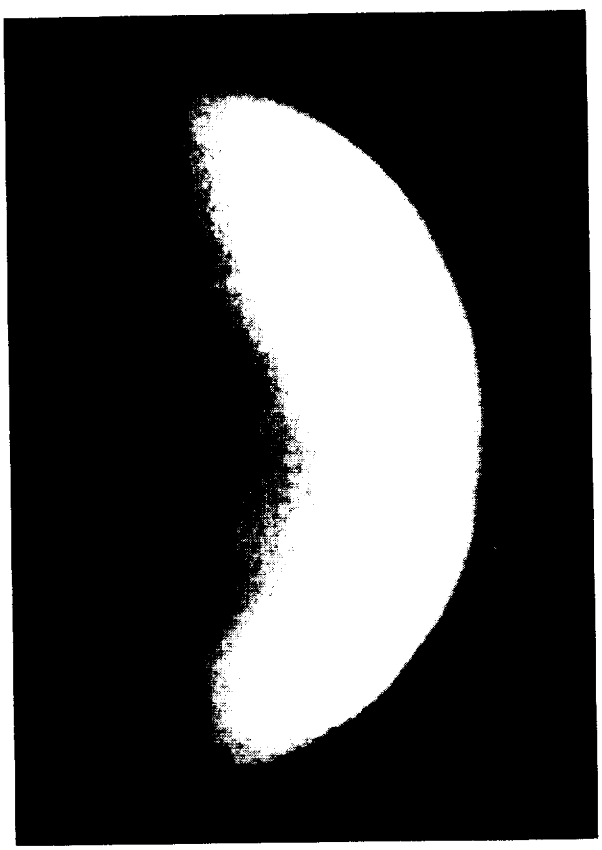


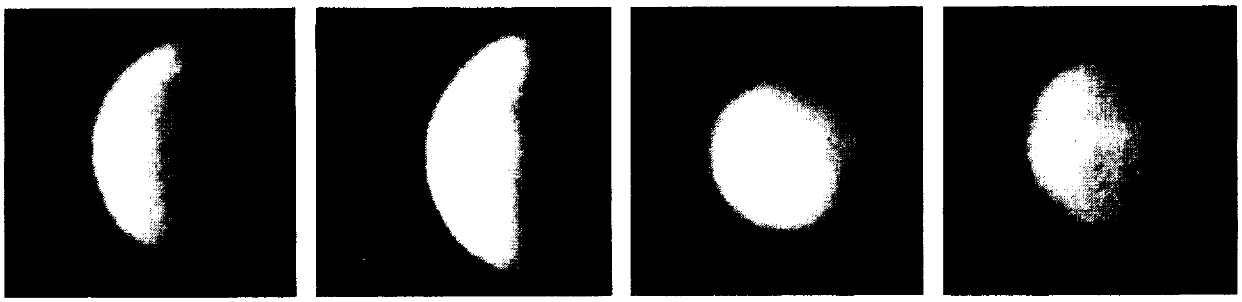
Fig. 1-6. Telescopic photographs of Venus from Earth show very little detail in the dense clouds that shroud the planet. Indistinct markings, seen in ultraviolet light, appear to rotate much faster than the planet itself.

Observations by a new mission were not expected to answer this fundamental question, but rather to provide some additional pieces of evidence toward solving the great puzzle. Particular attention was placed on designing a program of systematic observation of the mysterious ultraviolet markings discovered years before in telescopic observations of the planet. Although a telescope reveals virtually no visible details on the brilliant surface of Venus (Fig. 1-6), some observers recorded faint and elusive markings on photographs obtained with light in the near-ultraviolet region of the spectrum. These ill-defined, shadowy markings appeared to move around the planet in a period of a few days in the same direction as Venus's slow retrograde spin, established in 1961 by radar techniques to have a period of approximately 243 days.

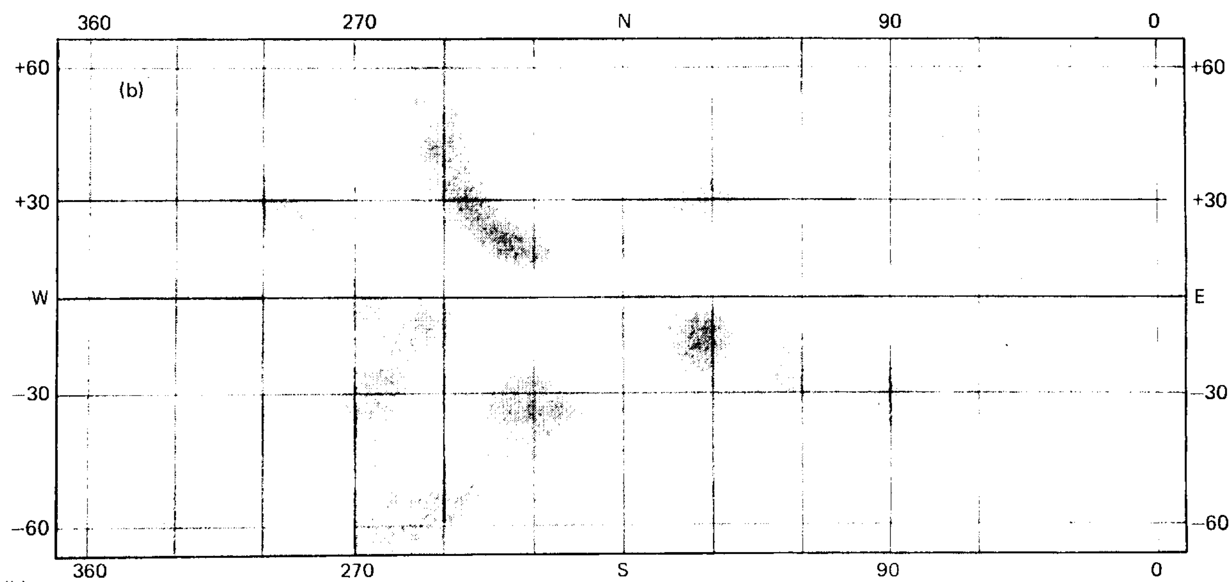
Closeup observations of the ultraviolet markings were desired to define their fine-scale morphology and verify their apparent rapid rotation rate. It was hoped that information of importance in developing an understanding of the dynamics of the upper atmosphere could be obtained. Detailed knowledge of the present state of Venus's atmosphere and the physical mechanisms operating within it are prerequisite to unravelling its evolutionary history. Further, such knowledge will aid significantly in developing a deeper perception of the fundamental mechanisms acting within the Earth's complex and dynamic atmosphere.

In addition to the major differences in atmospheric pressure and composition and spin rate, Venus's lack of a sensible magnetic field sets it apart from its sister planet. The nature of Venus's interaction with the solar wind, wherein the plasma impinges directly upon a dense atmosphere not enclosed in a "magnetic bottle," had been investigated by earlier spacecraft, but much remained to be learned by a new mission to Venus, particularly regarding the nature of the region far downstream which had not been probed by the earlier spacecraft.

Mercury, smallest of the planets except possibly Pluto, has an equatorial radius of 2439 km (1516 mi), making it intermediate in size between the Moon and Mars and smaller than two of Jupiter's satellites (Fig. 1-7). Until recently, astronomers thought that the closeness of Mercury to the Sun caused it to turn one hemisphere eternally sunward, just as the Moon turns one hemisphere evolved to their present states. The questions posed for Venus were sharply focussed, based upon a considerable body of knowledge. Those applied to Mercury were broad, exploratory, first-order: a reflection of what little was known of that tiny planet, so small and difficult to observe that the best estimate of generations of telescopic observers regarding its rotation rate had been proven wrong by radar experimenters only eight years earlier.



(a)



(b)

Fig. 1-8. Mercury, too, reveals few details, not because of clouds but because of the planet's small size, its distance from the Earth, and its closeness to the Sun. Photographs (a) show only indistinct shadings, and maps (b) made on the basis of observations from Earth are virtually useless.

toward the Earth. However, radio astronomers discovered in 1965 that Mercury rotates on its axis in 58 days. Coupled with the planet's 88-day period of revolution around the Sun, this rotation gives Mercury a solar day of 176 Earth days. Thus, one day on Mercury occupies two years of Mercury time.

Through a large telescope the planet presents a yellowish color broken by indistinct greyish patches (Fig. 1-8). On the basis of optical and infrared studies of Mercury, astronomers had long inferred that the planet would be cratered and without any appreciable atmosphere. Its density was known to be much more than the Moon, but rather close to that of Earth.

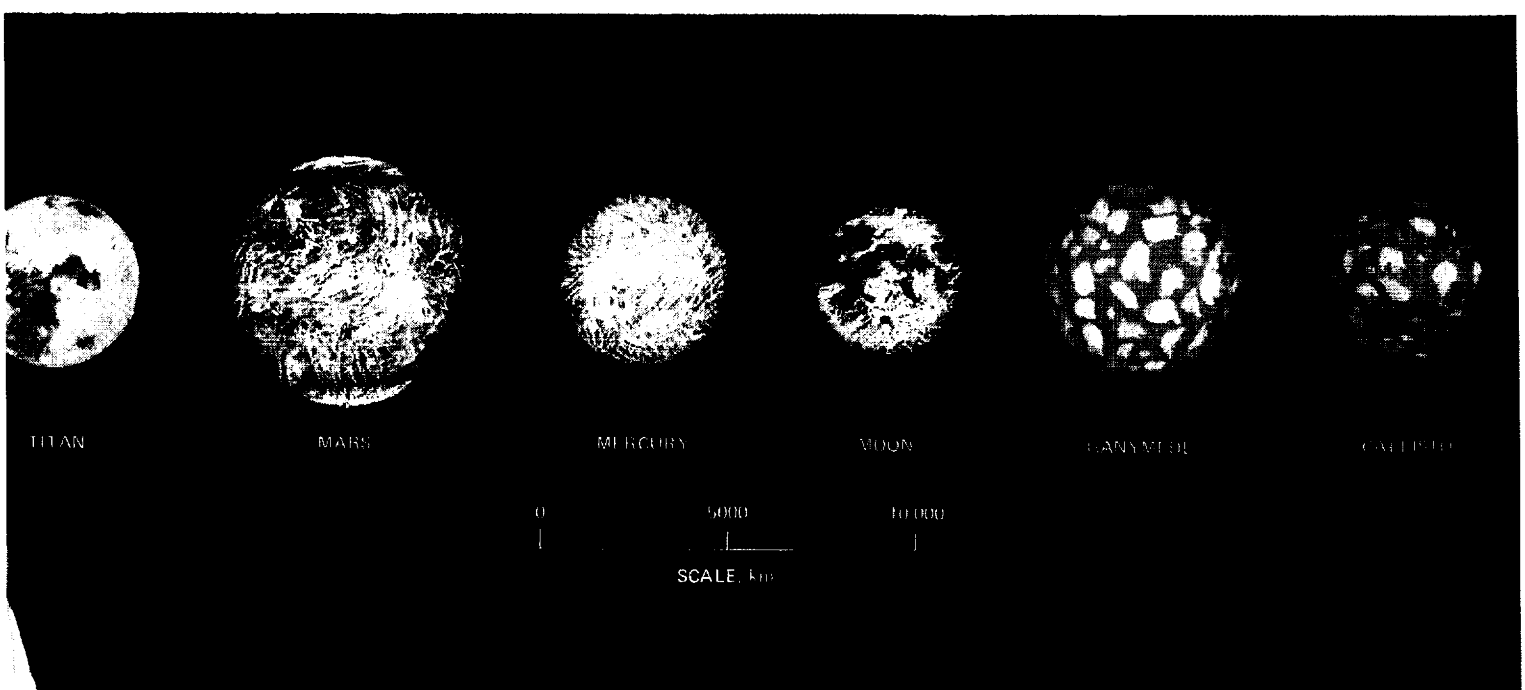
The innermost planet's importance to planetary science was known to be disproportionate to its size. Earth-based observations at radar, visible, and infrared wavelengths had strongly suggested the absence of any atmosphere, and it was therefore hoped that a primordial surface, upon which was written a history of the early events in the inner Solar System, unerased by the action of wind and water, awaited a spacecraft's cameras. The opportunity to study this anticipated record was eagerly awaited because, should Mercury's primordial surface remain, a valuable comparison with similar surfaces on the Moon and Mars could be made, providing an insight into the distribution of the planetesimals whose impacts on these other two bodies had left a record in their cratered terrains. Furthermore, the probable location of the source of these bodies could be better understood by a careful analysis of the cratering densities on the three bodies.

Mercury's importance to planetary science was not restricted to the expected record of late stage formational events, however. The planet's high density, equivalent to that of the Earth, has long been of interest to theoreticians concerned with the formation of the inner planets. Because of Mercury's small size, the high density must reflect a metal-rich composition. What clues could Mariner provide as to the internal composition of Mercury? In particular, is the planet chemically differentiated? If so, when did this differentiation occur? The answers to these question would be significant with regard to theories of chemical evolution of the terrestrial planets.

Clues regarding Mercury's internal composition were expected to be obtained from the several instruments designed to study its interaction with the solar wind, the details of which depend upon gross planetary properties like atmospheric composition and pressure, the presence or absence of a magnetic field, bulk conductivity, and so on. Further information was expected from a study of the composition and structure of the planet's presumably tenuous atmosphere, expected to be less than a thousandth of the Earth's total pressure.

Thus, a mission to Venus and Mercury would have as its goal the acquisition of previously unavailable fundamental information on both planets—a few more pieces of the puzzle of how the planets, including the Earth, formed and

Fig. 1-7. In comparison, Mercury is between the Moon and Mars in size. Some satellites of the outer planets are equally as large.



Chapter 2

Mariner Venus-Mercury Mission

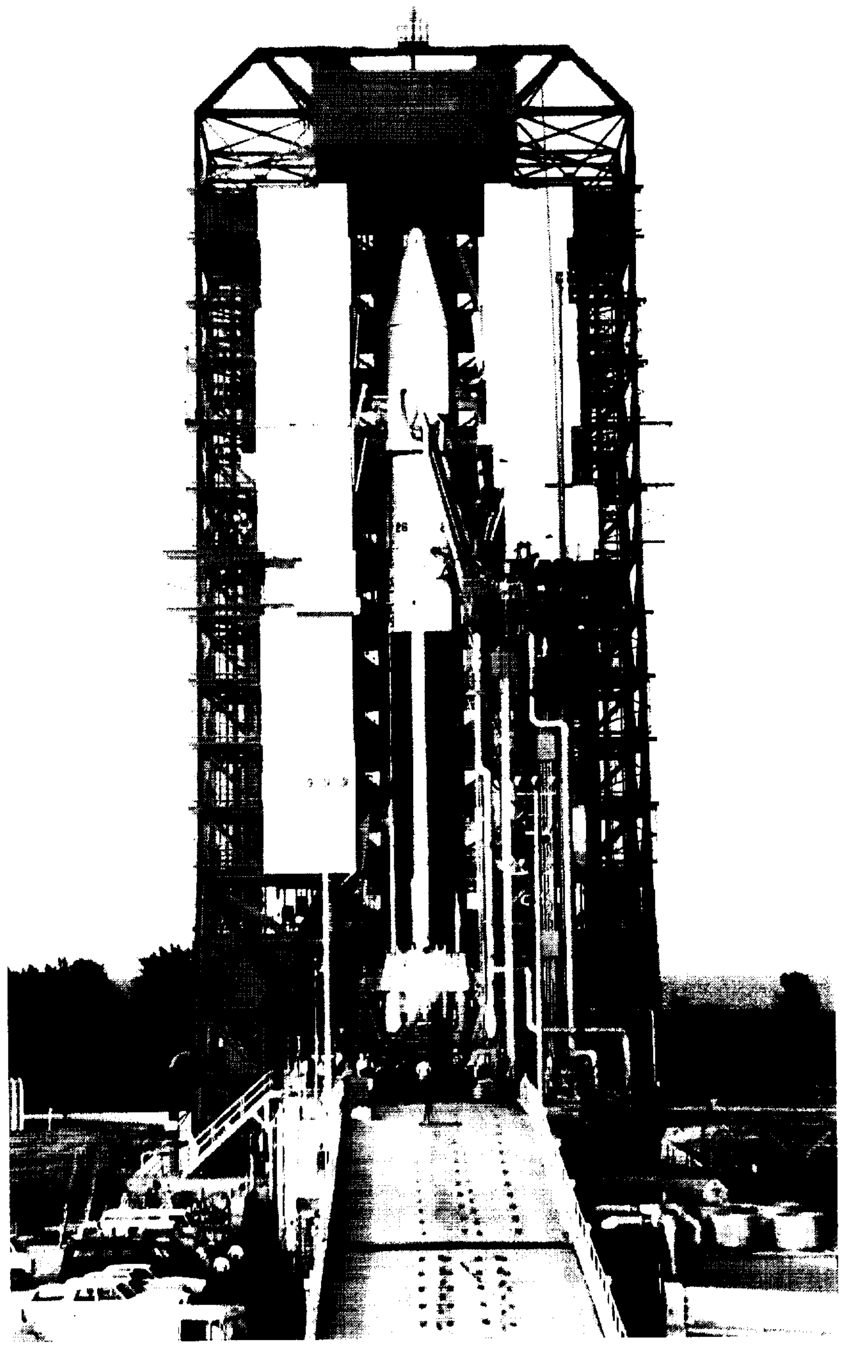
THE GRAVITY-ASSIST trajectory technique which was needed to obtain an economically acceptable mission to Mercury resulted from over 20 years of speculation, scientific research, and engineering development. The technique allows a spacecraft to change both its direction and speed without expenditure of propellant, thereby saving time and increasing scientific payload on interplanetary missions. By its use an acceptable payload could be launched to Mercury by an Atlas/Centaur. The much larger and more costly Titan III C/Centaur would be required for a direct flight to the innermost planet.

The concept of gravity-assist interplanetary missions first received serious attention in the literature of the 1950's, though multiple-planet orbits had been considered during the 1920's and 30's.

In the following years the concept was utilized mainly in studies of round-trip interplanetary flights in which the spacecraft leaves the Earth, flies by several planets, and returns to Earth. The first systematic development of the gravity-assist technique was performed at the Jet Propulsion Laboratory, Pasadena, California, in the early 1960's. Previously, such multiple-planet trajectories had been sought by inspecting computer-generated listings of parts of flight paths, such as the Earth-Venus and Venus-Earth components, and matching them in regard to velocities and time. An Earth-Venus-Earth round trip had been discovered by this method, and JPL trajectory designers next developed a mathematical technique for searching out gravity-assist trajectories so that they were able to program the equations for processing on a digital computer. They soon discovered the existence of Earth-Venus-Mercury trajectory opportunities for 1970 and 1973, but found that the gravity-assist trajectory was extremely sensitive to errors in aiming the spacecraft toward the first planet, suggesting that a new kind of guidance might be necessary to make the technique practicable. Further analysis revealed, however, that there were actually no barriers in contemporary guidance technology to prevent a multiple-planet mission. As a result, detailed plans and a navigation strategy for the 1970 Venus-Mercury opportunity were prepared, establishing its practical feasibility as a space mission.

Early in 1970, Guiseppe Colombo of the Institute of Applied Mechanics in Padua, Italy, who had been invited to JPL to participate in a conference on the Earth-Venus-Mercury mission, noted that in the 1973 mission the period of the spacecraft's orbit, after it flew by Mercury, would be very close to twice the period of Mercury itself. He suggested that a second encounter with Mercury could be achieved. An analytical study conducted by JPL confirmed Colombo's suggestion and showed that by careful choice of the Mercury flyby point, a gravity turn could be made that would return the spacecraft to Mercury six months later.

Fig. 2-1. The Atlas/Centaur provided the necessary launch capability for the Venus swingby to Mercury.



In June 1968, the Space Science Board of the National Academy of Science completed a planetary exploration study in which the mission to Mercury via Venus was endorsed. The Board recommended that a 1973 launch opportunity be aimed for and suggested some of the scientific experiments that might be carried out on the mission.

Approved by NASA in 1969, the mission which resulted from this recommendation involved the scientific community early enough for scientists to contribute to decisions concerning design of the spacecraft and selection of its subsystems. The possibility of later conflict between mission constraints and science needs would thereby be reduced.

The National Aeronautics and Space Administration selected a group of scientists to represent the several disciplines that would be involved in the science payload of a mission to Mercury via

Venus, and a Science Steering Group was officially formed in September 1969. Its purpose was to recommend objectives for and plan a good science mission within tight monetary constraints, coordinating the requirements of teams for the individual instruments and participating in project design and tradeoff studies relevant to mission, spacecraft, and flight operations.

In January 1970, a Mariner Venus/Mercury project office was established at JPL, under the direction of Project Manager Walker E. Giberson. Experiments were selected by July 1970, and by July 1971 a contract was negotiated with the Boeing Company, Kent, Washington, for design and fabrication of two spacecraft: a flight spacecraft and a test spacecraft.

Overview of the Mission

The mission plan called for launching the spacecraft with an Atlas SLV-3D/Centaur D-1A launch vehicle (Fig. 2-1) between October 16 and November 21, 1973. From such a launch window the spacecraft could encounter Venus between February 4 and 6 and Mercury between March 27 and 31, 1974.

The proposed trajectory relied upon Venus's gravitational field to alter the spacecraft's flight path and speed relative to the Sun, such that the reduction in velocity would cause the spacecraft to fall closer to the Sun and therefore to cross Mercury's orbit at the exact time needed to encounter the planet (Fig. 2-2). Closest-approach altitudes at Venus and Mercury would be 5000 and 1000 km (3100 and 620 mi), respectively.

To meet the demands of the gravity-assist technique, Mariner Venus/Mercury had to be launched on an orbit around the Sun that would intercept the planet Venus with high precision. The spacecraft could not carry sufficient propellant for very large maneuvers after the encounter with Venus, and the trajectory to Venus demanded new levels of accuracy. At least two maneuvers to correct the trajectory would be needed between Earth and Venus and two more between Venus and Mercury. Flyby of Venus had

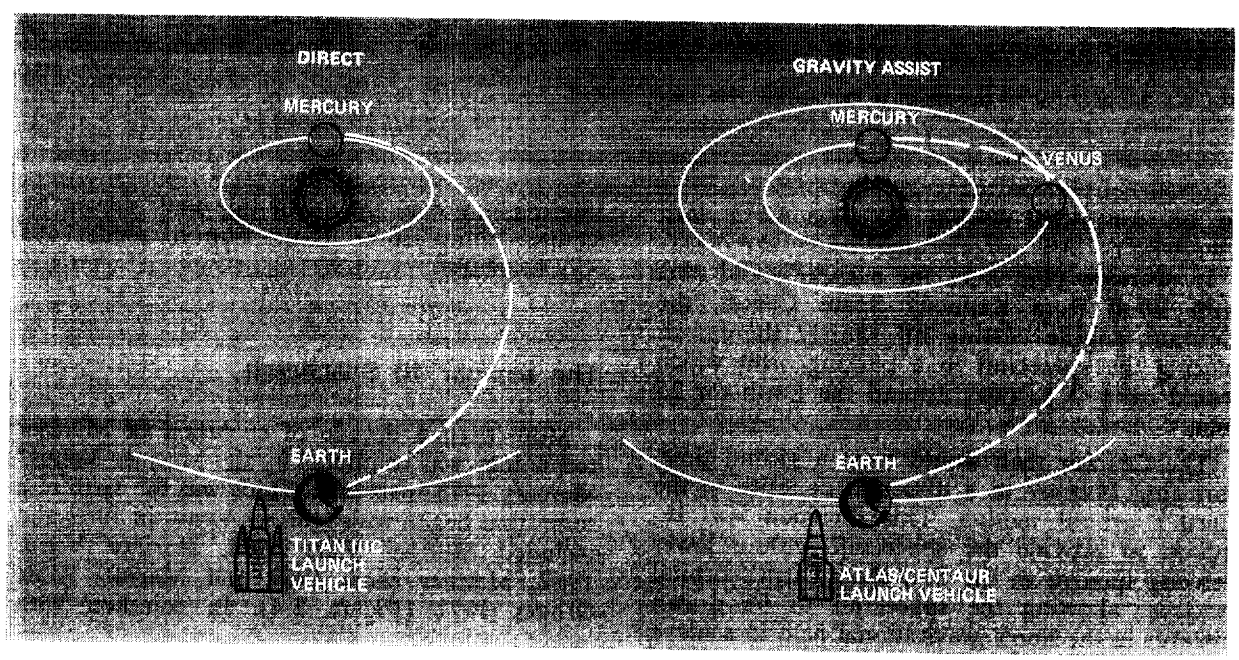


Fig. 2-2. The gravity-assist trajectory to Mercury uses the gravity and orbital motion of Venus to provide a slingshot that hurls a spacecraft into the inner Solar System without further use of propellants except for minor corrections to the trajectory. A direct flight to Mercury would require a much larger launch vehicle to deliver the same payload of scientific instruments without this Venus assist.

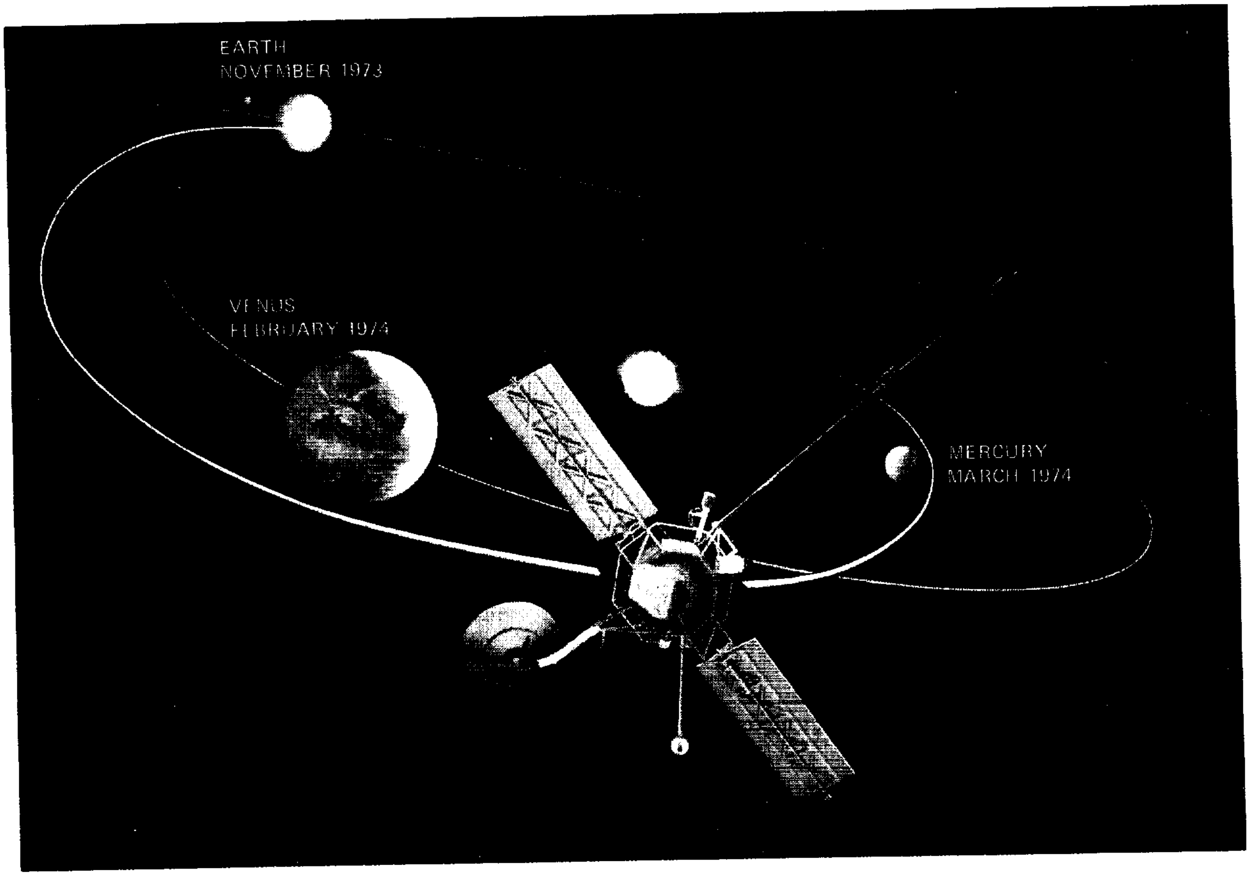


Fig. 2-3. Times of launch and arrival at the planets were clearly defined.

to be controlled within 400 km (250 mi), otherwise no Mercury encounter could take place.

In overview (Fig. 2-3), the mission would start with liftoff from Kennedy Space Center, the Centaur engine cutting off shortly thereafter, placing the spacecraft in a parking orbit which would carry it partway around the Earth for 25 min.

The Centaur then would burn a second time, thrusting Mariner in a direction opposite to the Earth's orbital motion. This direction was required to provide the spacecraft with a lower velocity relative to the Sun than Earth's orbital velocity, allowing the spacecraft to be drawn inwards in the Sun's gravitational field to achieve its encounter with Venus.

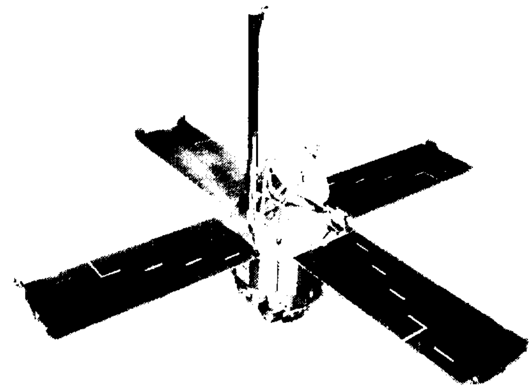
A few months later the Mariner spacecraft would approach Venus from the planet's dark side, passing over the sunlit side and, slowed by Venus, falling closer to the Sun to rendezvous with Mercury.

The Mariner 10 Spacecraft

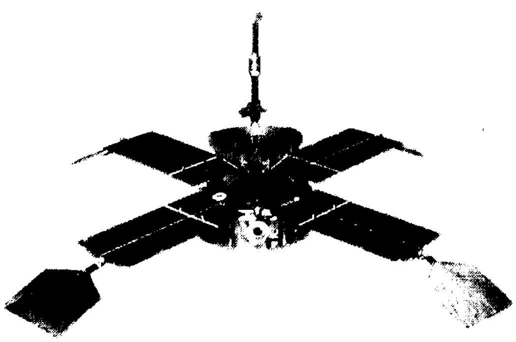
More than a decade of evolution of Mariner technology was continued by the Mariner Venus/Mercury 1973 spacecraft, which was the sixth of a series that began with Mariner Venus in 1962 and included Mariner Mars 1964, Mariner Venus 1967, Mariner Mars 1969 and Mariner Mars Orbiter 1971 (Figure 2-4). In common with

Fig. 2-4. Mariner Venus/Mercury continued a line of successful Mariner spacecraft that had previously explored Venus and Mars.

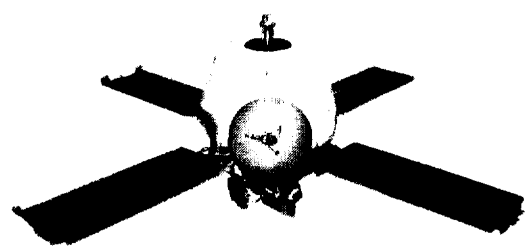
MARINER 2
VENUS 1962



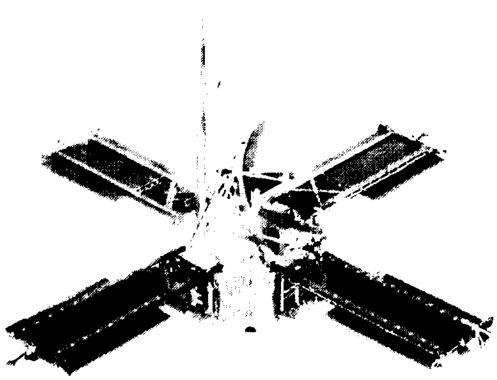
MARINERS 6 AND 7
MARS 1969



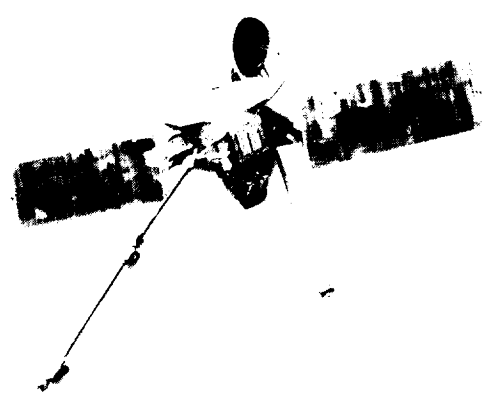
MARINER 4
MARS 1964



MARINER 9
MARS 1971



MARINER 5
VENUS 1967



MARINER 10
VENUS AND MERCURY 1973

earlier spacecraft, it used an octagonal main structure, solar cells and a battery for electrical power, three-axis attitude stabilization and control by nitrogen gas jets, celestial references by star and Sun sensors, S-band radio for command, telemetry, and ranging, a high-gain antenna, a low-gain antenna, a scan platform to point science instruments, and a hydrazine rocket propulsion system for trajectory corrections. The spacecraft was designed to fit folded into the launch configuration of the Atlas SLV-3D/Centaur D-1A launch vehicle ready to unfold its appendages and sensors when it reached space.

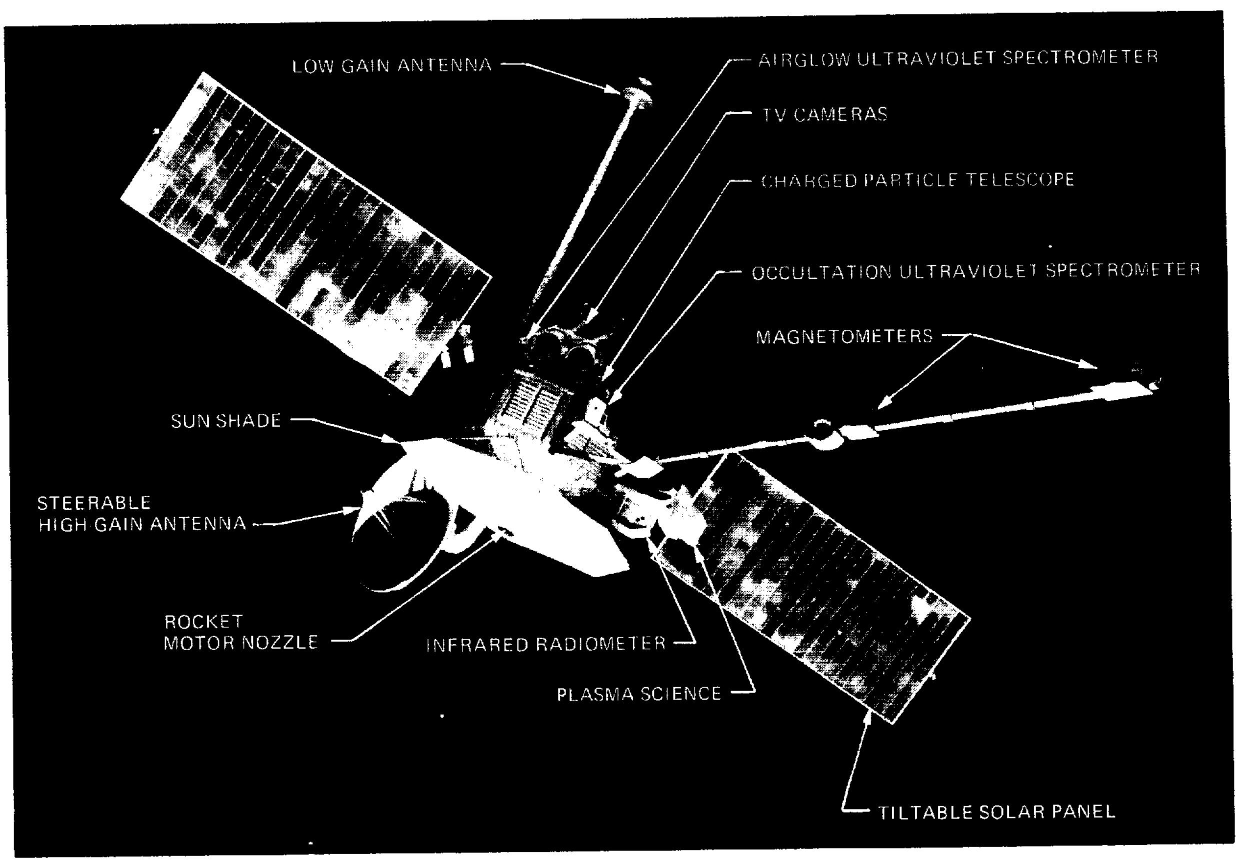
Figure 2-5 shows the relative arrangements of major parts of the Mariner spacecraft: basic structure, power and thermal control, telecommunications and data, navigation and orientation, and scientific payload.

Launch weight of the spacecraft was 533.6 kg (1175 lb), including 29 kg (64 lb) of hydrazine propellant and 30 kg (66 lb) associated with the adapter to the launch vehicle. The payload of scientific instruments weighed 78 kg (172 lb).

Subsystems included equipment to modulate and demodulate electrical signals, generate, store, and distribute power, handle flight data, control spacecraft attitude, release mechanical devices, propel the spacecraft, control temperature, articulate and point spacecraft devices, store data onboard the spacecraft, and communicate with Earth. There was also a central computer and sequencer. All these subsystems together with mechanical devices used for deployment supported the science experiments.

Some changes to the Mariner concept were needed for the mission to Mercury, principally

Fig. 2-5. The Mariner Venus/Mercury spacecraft consists of several basic parts, each one essential to the success of the mission. These include its basic structure, power and thermal control, telecommunications, navigation, propulsion, orientation, and science payload. Solar cells provide electrical energy for the spacecraft power system.

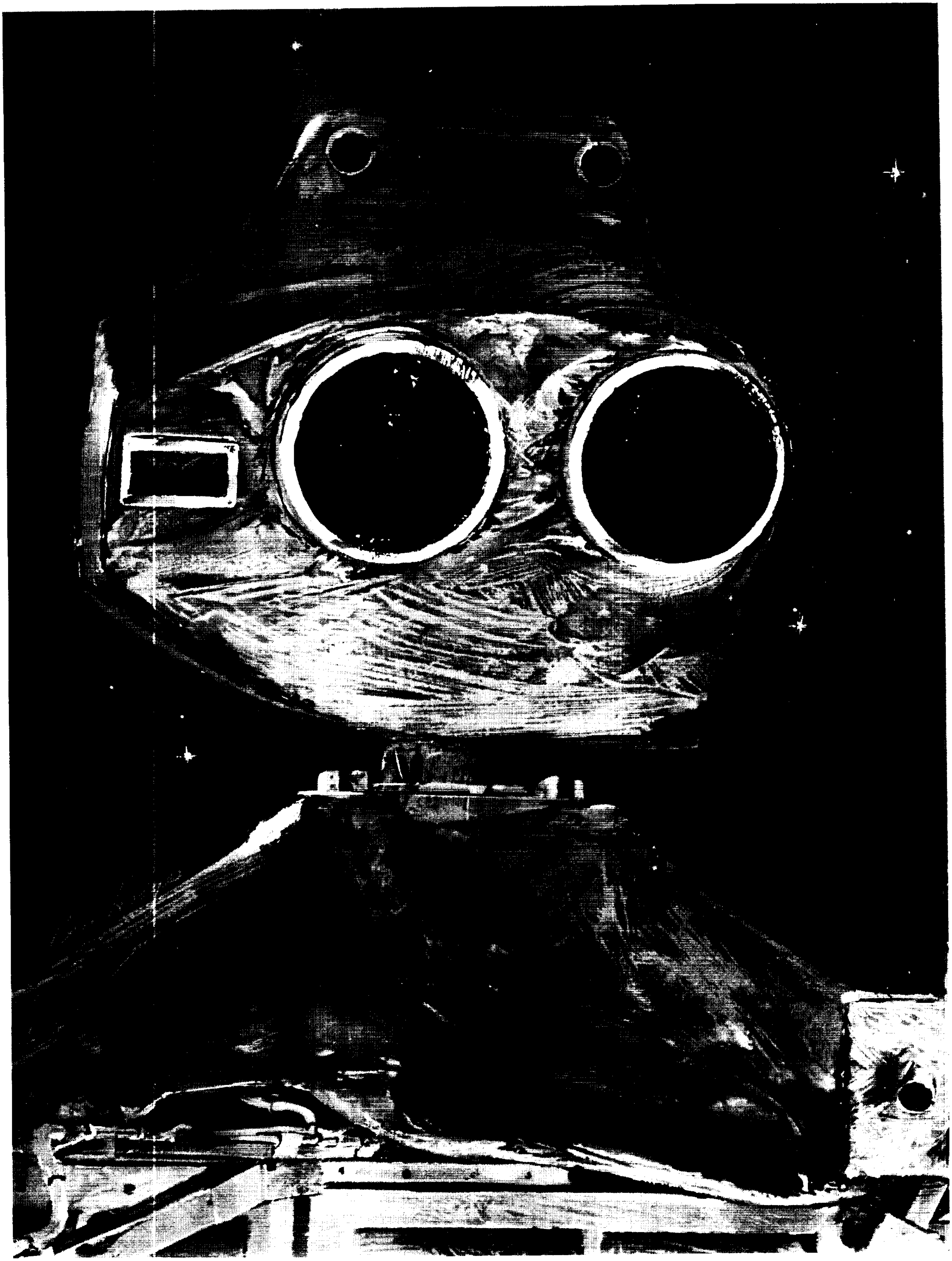


because the spacecraft had to approach the Sun much closer than any previous planetary spacecraft. This required improved ways to insulate the spacecraft from solar radiation. Thermal control of the new Mariner had to protect it from solar intensities up to 4 1/2 times that incident upon the Earth. Thermal control required, in addition to a large sunshade, louvers and protective thermal blankets, the ability to rotate the solar panels about an axis that ran along their length. By changing the angle at which the sunlight shone on the panels, the solar cells were kept at a suitable temperature—about 115°C (239°F)—as the spacecraft approached closer to the Sun. Both panels could turn up to a total of 76 deg from directly facing the Sun and could be rotated individually in fine steps. Other major design changes from past Mariners included the addition of a capability to handle up to 118 thousand bits per second of TV data and 2450 bits/sec for nonimaging science and engineering data as well as the capability for both S- and X-band ranging and X-band carrier transmission. Also, a central flight data subsystem for science and engineering data processing and science control allowed engineering format to be reprogrammed in flight and provided 21 data modes for television, nonimaging science, engineering, and data storage playback.

In addition, the new Mariner had a central articulation and pointing subsystem for its scan platform, its two-degree-of-freedom high-gain antenna, and its tiltable solar panels, with either closed-loop positioning or discrete incremental command capability. Finally, the propulsion system had to be capable of multiple firings, in order to accommodate the number of in-flight trajectory correction maneuvers required for precise navigation.

All the subsystems were designed on the basis of using both Mariner residual hardware as well as Mariner technology. The tight budget constraint on the program made it necessary to use proven techniques to keep development costs low. This was achieved by applying existing hardware or existing designs with such modifications as were needed, making best use of earlier Mariner hardware units by upgrading existing prototypes, and eliminating many of the traditional spares by using the qualification test unit as either a spare or a flight unit.

As planning for the mission became more detailed and revisits to Mercury in an extended mission more attractive, spacecraft design decisions were made accordingly. While the basic spacecraft design concept was not initially intended for such an extended mission, once that mission had been accepted as a possibility, design alternatives were chosen that would not rule it out. Thus, when alternatives presented themselves, and costs were the same, that alternative was picked which favored the extended mission. Major decisions that had great significance ultimately to the capability for multiple Mercury encounters were to increase the amount of attitude control nitrogen gas carried by the spacecraft and to incorporate the capability to rotate the panels in both directions so that the solar panel angles could be decreased as well as increased, allowing operation beyond the first Mercury encounter.



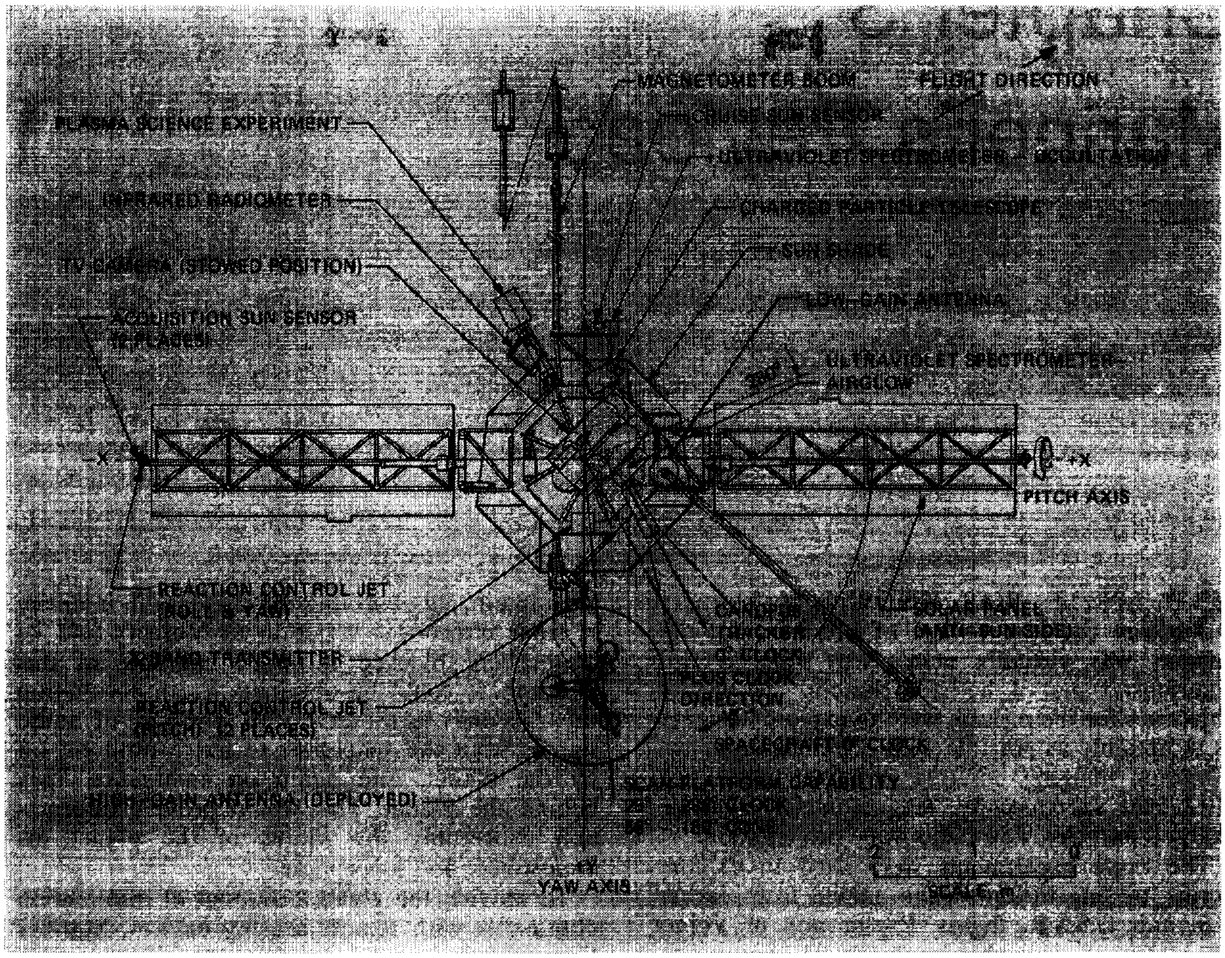


Fig. 3-1. Mariner Venus/Mercury carried a battery of science instruments.

scan platform, could be pointed on command. This "airglow" spectrometer was used to scan both of the planets, searching for evidence of hydrogen, helium, argon, neon, oxygen, and carbon. At Venus, it searched for specific gases, and during the cruise phase it looked for sources of ultraviolet radiation coming from hot stars and gas clouds in the galaxy. Measurements were also made of the gaseous envelope surrounding the comet Kohoutek.

A complex of two televison cameras with eight filters was the basis of the imaging experiment. These cameras were capable of taking both narrow- and wide-angle views of Venus and Mercury. Sharing the scan platform with the airglow spectrometer, the imaging complex was directed by command from Earth. As well as taking pictures in different colors of light, these cameras also measured how the light was polarized, observations intended to provide information on the composition of the clouds of Venus and the surface of Mercury.

A radio experiment used the signals transmitted from the spacecraft to Earth. By tracking the spacecraft signals, experimenters determined how the spacecraft was affected by the gravitational fields of the planets. From this information they determined the shape of each planet and whether there were anomalies in its gravitational field.

By analysis of what happened to the radio signals as they passed close to the limb or edge of the planet, experimenters were able to probe the

Chapter 3
Mariner's Payload

SO LITTLE WAS KNOWN of Mercury before the epic voyage of Mariner that the mission was virtually man's first look at this innermost planet of the Solar System. The science objectives for the mission were to explore Mercury as thoroughly as possible with seven experiments: television imaging, infrared radiometry, extreme ultraviolet spectroscopy, magnetometer, plasma, charged particles, and radio wave propagation.

The same experiments were used to explore Venus, adding to knowledge gained from earlier U.S. and U.S.S.R. flights. Exploration of Venus was restricted somewhat by the trajectory requirements for reaching the prime target, Mercury. These requirements made it necessary, for example, for Mariner to follow a trajectory that did not produce a Sun occultation at Venus, so the ultraviolet occultation experiment (see page 24) could not be conducted at that planet.

To obtain best science results, the objectives of each experiment were established and the space near Mercury was evaluated for aiming points and trajectories that would satisfy them. Of major importance was a flight path that would place the planet between the spacecraft and the Sun, and also between the spacecraft and the Earth, i.e., solar and Earth occultation, respectively.

Study of the planet's effect on the Sun's plasma gas and magnetic fields ("solar wind") required a solar occultation, as did the sounding of Mercury's atmosphere by the ultraviolet occultation experiment. By observing the decrease in intensity of solar ultraviolet radiation as Mercury and its atmosphere blocked it out, a measure of this atmosphere could be obtained. Earth occultation was needed to observe the passage of radio signals from the spacecraft to Earth until cut off by the planet, and again on emergence from behind the planet. This would provide information concerning the radius of the planet, its atmosphere and ionosphere.

To provide the greatest amount of information obtainable with remote sensing devices, Mariner Venus/Mercury carried more science instruments (Fig. 3-1) than most previous Mariner spacecraft. A magnetometer measured magnetic fields, a plasma analyzer measured the ions and electrons of the solar wind, and cosmic ray telescopes provided information on solar and galactic cosmic rays. The main objective of these instruments was to learn about a planet by studying its effects on the interplanetary medium.

An infrared radiometer measured temperatures of the clouds of Venus and the surface of Mercury. Two independent ultraviolet instruments (measuring light beyond the violet end of the spectrum) analyzed the planetary atmospheres. One instrument was fixed to the body of the spacecraft and was used at Mercury to search for traces of atmosphere along the edges of the visible disc of the planet. A second instrument, mounted along with the television cameras on a atmosphere of Venus and check for an atmosphere of Mercury. To take full advantage of the Venus occultation, which bent the radio signals appreciably, the high-gain antenna on the spacecraft was steered so as to compensate partially for the bending of the radio signal. In this way, information was obtained at deeper levels of the atmosphere than was possible with earlier flyby spacecraft.

The science experiments were selected from proposals submitted to NASA in response to the announcement of the Mariner Venus/Mercury flight opportunity.

Infrared Radiometer

This instrument measured temperatures on the surface of Mercury and the clouds of Venus by sampling thermal (infrared) radiation. Observations of thermal emission from Mercury were expected to provide information on the average thermal properties, large-scale and small-scale surface anomalies, and surface roughness. It was known that temperature variations on Mercury would be large, owing to intensive heating of the day side and the slow rotation period of 58.6 days, which allows the night side to radiate away most of its heat. Measurement of heat absorption and loss across the terminator (shadow line) regions could provide indirect evidence of the nature of the surface material: such as whether it is sand, gravel, or rock. At Venus the instrument was expected to provide cloud top brightness temperatures at higher resolution than can be achieved from Earth or had been achieved by earlier spacecraft.

The infrared radiometer was fixed to the body of the spacecraft on the sunlit side, with apertures shielded from the direct sunlight under a thermal blanket. The instrument (Fig. 3-2) was based upon earlier radiometers flown on Mariner Mars 1969 and 1971, but instead of the reflecting optics of the earlier radiometers, the new instrument made use of two Cassegrain telescopes with special long-wavelength filters. This allowed observations at longer wavelengths and also increased sensitivity.

Two 1/2-deg fields of view separated by 120 deg were used to scan Mercury, the angular separation being obtained by a three-position scan mirror (see Fig. 3-3). The forward and aft

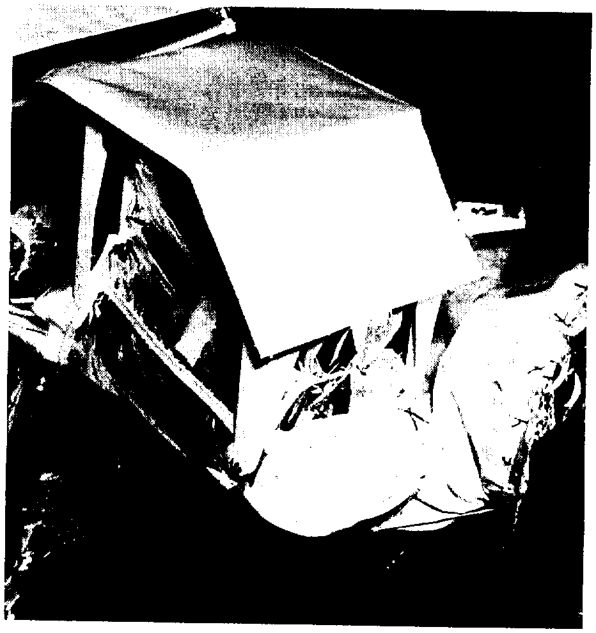


Fig. 3-2. An infrared radiometer measured temperatures of the clouds of Venus and of the surface of Mercury.

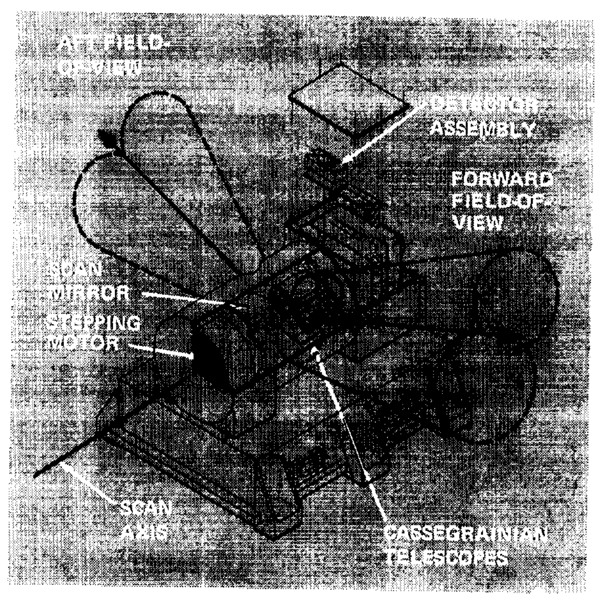
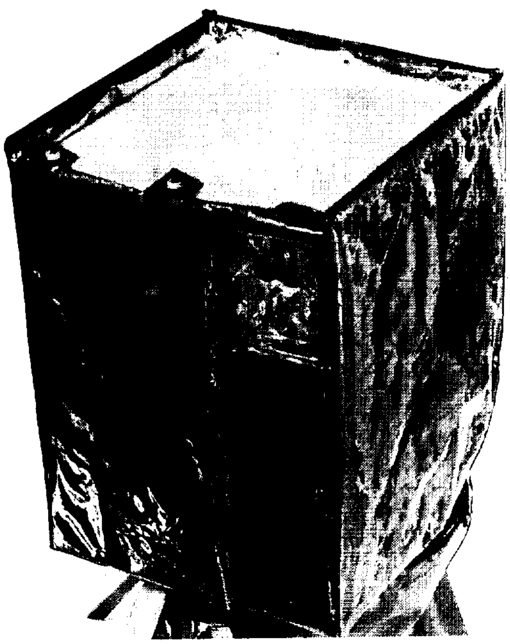
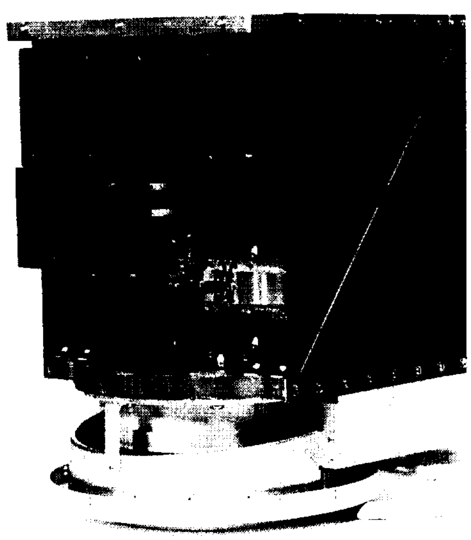


Fig. 3-3. The radiometer used a three-position scan mirror so that it could compare radiation from the planet with that from the dark sky.

viewing beams thus ensured that there could be both a planet viewing beam and a black space reference beam for all the observations.

The instrument measured surface brightness temperature in the two spectral bands 34 to 55 and 7.5 to 14 micrometers, which correspond to temperature ranges of 80 to 340 and 200 to 700 K, respectively.



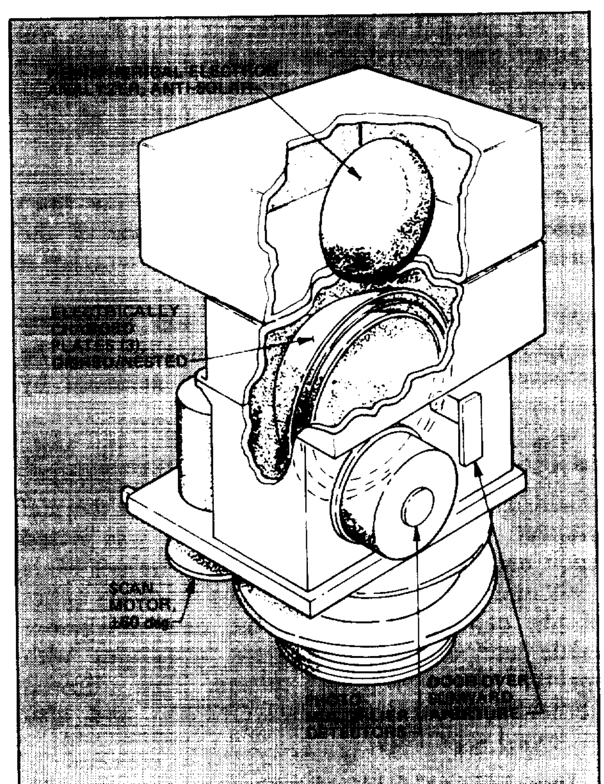


Plasma Science

Observations of the velocity and the directional distributions of the normal solar wind constituents in the vicinity of Mercury were required to understand the interaction of the solar wind with the planet. Observations of the solar wind inside the orbit of Venus were also important, since no previous spacecraft had penetrated this region. Therefore, continuous measurements were planned from the orbit of the Earth to the orbit of Mercury. Additionally, an objective of the experiment was to verify and extend previous observations of the solar wind's interactions with Venus and to clarify the role of electrons in these interactions.

Instrumentation for the experiment consisted of two detectors on a motor-driven platform (Fig. 3-4). The principal detector, facing sunward,

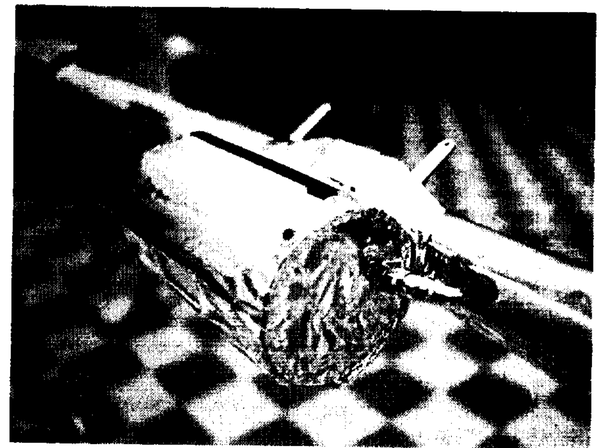
Fig. 3-4. A plasma science experiment relied upon two detectors mounted on a scan platform. The scanning electrostatic analyzer consisted of three hemispherical plates directed toward the Sun to measure incoming electrons and positive ions.



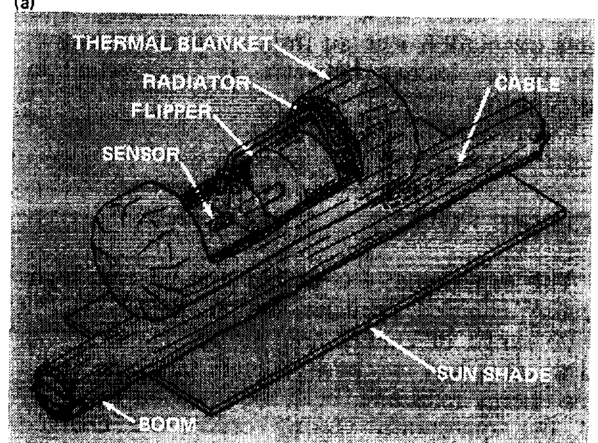
consisted of a pair of electrostatic analyzers. The auxiliary detector, facing away from the Sun, was a single electrostatic analyzer. The forward looking device was called the scanning electrostatic analyzer while the backward looking device was called the scanning electron spectrometer. The former measured positive ions and electrons, the latter only electrons.

The importance of investigating the interaction of the solar wind with the planets and the variation of the wind with distance inside the orbit of Venus was evidenced by the large team of investigators selected from seven research organizations for this experiment.

The solar wind is an extension of the Sun's corona into interplanetary space. It is a fully ionized gas which consists of equal numbers of positively charged particles (mostly protons) and negative electrons. This ionized gas or plasma moves radially outward from the Sun at a very high velocity, hundreds of kilometers per second. The magnetic field of the Sun is carried outward by the plasma and is bent into a spiral configuration by a combination of the radial motion of the plasma and the rotation of the Sun. If one thinks of the plasma as a hot, ionized gas, the ions and electrons have two sorts of motions: a bulk velocity because they are both streaming outward from the Sun, and a thermal velocity because the gas is hot. For the protons, the bulk velocity is much higher, about a factor of 10, than the average thermal velocity; for electrons, the situation is exactly reversed. To an observer on the spacecraft, the positive ions appear to come almost directly from the Sun, whereas the electrons come almost uniformly from all directions. To study the properties of the plasma, the combined experiments were mounted at the end of a short boom, on a platform which allowed the plasma experiment to scan right or left through an angle of 60 deg above and below the spacecraft-Sun line.



(a)



(b)

Fig. 3-5. A magnetometer experiment used two three-axis sensors mounted on a long boom extending from the spacecraft. Two sensors were used to isolate the magnetic field of the spacecraft itself: (a) shows one of the sensors mounted on the boom; (b) is a diagram of a sensor.

Magnetic Field Experiment

The magnetic field experiment consisted of two 3-axis sensors located at different positions along a 6.1-m (20-ft) boom. Figure 3-5 shows a magnetometer mounted on the boom, together with a cutaway view of a sensor. The two sensors carried on the boom were triaxial fluxgate magnetometers. Each sensor was protected from direct solar radiation by a sunshade and a thermal blanket. The purpose of the two sensors was to permit the simultaneous measurement (at different distances from the spacecraft) of the magnetic field, which is the sum of the weak magnetic field in space (and near the planets) and the magnetic field of the spacecraft itself. The inboard magnetometer, being approximately twice as close to the spacecraft as the outboard sensor, was more sensitive to changes in the magnetic field of the spacecraft, with the result that these perturbations could be isolated and removed from the outboard sensor measurements.

In interplanetary space, the magnetic field is typically about 6 gamma (compared with the strength at Earth's equator on the surface of 30,000 gamma). By contrast, the field of the spacecraft, as measured at the outboard sensor, was observed to vary in direction and intensity quite considerably during the mission, swinging from 1 to 4 gamma. This variation in the spacecraft field demonstrated the importance of having two sensors to remove the spacecraft field from the measured field. In addition to the planetary observations, magnetic field observations were important in studying how the interplanetary plasma varies with distance from the Sun and how this plasma moves outward from the Sun. The measurements of plasma and magnetic fields were mutually supporting, and their correlation was an important and sensitive test of consistency between the two scientific instruments.

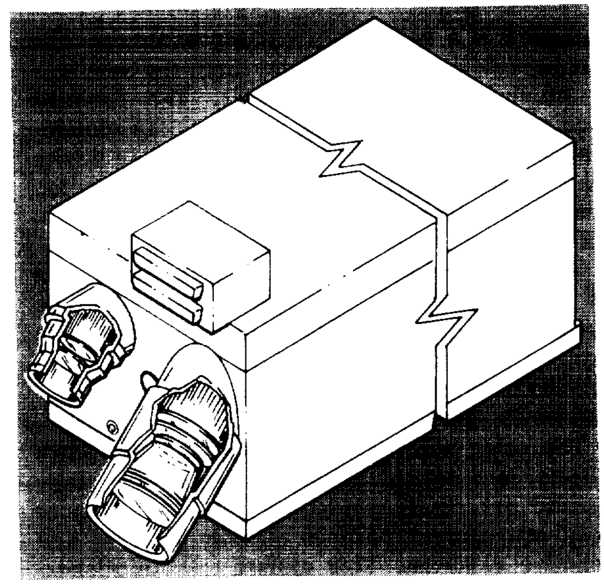


Fig. 3-6. Charged particles accelerated to high energies were detected by two high-energy particle telescopes. This experiment was designed to determine how the solar wind interacts with the planets.

Charged Particles

This experiment was designed to observe high-energy charged particles—atomic nuclei—over a wide range in energy and atomic number. The instrument had two parts, a main telescope and a low-energy telescope, both mounted on the body of the spacecraft. During cruise the charged particle experiment measured solar and galactic cosmic rays with the objective of determining the effect of the Sun's extended atmosphere (heliosphere) on cosmic rays coming into the Solar System from elsewhere in the galaxy. During encounter with Mercury, the experiment was to search for charged particles in the vicinity of Mercury. The effect of solar flares on the flux of charged particles was correlated with measurements made from Pioneer spacecraft in the inner and outer Solar System as well as IMP (Interplanetary Monitoring Platform) spacecraft circling the Earth to determine how solar particles propagate in interplanetary space. The instrument is shown in Fig. 3-6. The two telescopes looked 45 to 50 deg west of the line from spacecraft to the Sun, with a 70-deg field of view. The low-energy telescope allowed the separate detection of relatively low-energy protons in the range 0.4 to 9 MeV (million electron volts) and alpha particles (helium nuclei) in the range 1.6 to 25 MeV.

The high-energy telescope detected electrons in the range 200 KeV (thousand electron volts) to 30 MeV, protons of energy greater than 0.55 MeV, and uniquely detected alpha particles with energy greater than 40 MeV. Both telescopes were able to detect energetic nuclei of atomic numbers up to oxygen.

The telescopes were very similar to those flown in Pioneer 10 and 11 to the outer Solar System. In fact, when Mariner reached Mercury for a first encounter, Pioneer 10 was more than five times the distance of the Earth from the Sun and Pioneer 11 3.5 times the distance from the Sun. Thus the three spacecraft provided an unprecedented range of radial measurements of the modulation of the cosmic ray flux by the heliosphere.

Extreme Ultraviolet

This experiment consisted of two independent instruments: a fixed solar-looking occultation spectrometer, mounted on the body of the spacecraft, and an airglow instrument, mounted on the scan platform. The aim of the experiment was to analyze planetary atmospheres, and, during cruise, to measure distribution of hydrogen and helium Lyman-alpha radiation emanating from outside the Solar System.

The search for an atmosphere on Mercury represented a primary scientific objective of this experiment. The extreme ultraviolet spectrometers provided two approaches to this search. The first observed the occultation of the Sun by the disc of Mercury; the other scanned through the atmosphere on both bright and dark limbs in search of emission from the neutral constituents hydrogen, helium, carbon, oxygen, argon and neon, at wavelengths ranging from 304 to 1659 angstroms. These elements were selected for study on the basis of theoretical prediction of the most likely constituents of the presumably tenuous atmosphere of Mercury.

The occultation spectrometer (Fig. 3-7) was set to be responsive at four spectral bands, centered at 475, 740, 810, and 890 angstroms, where the relatively high solar ultraviolet intensity and the large absorption cross section of all gases in this spectral region would combine to provide highly sensitive measurements of the atmosphere of Mercury, independent of its composition.

The airglow experiment (Fig. 3-8), in addition to providing a measurement of the relative

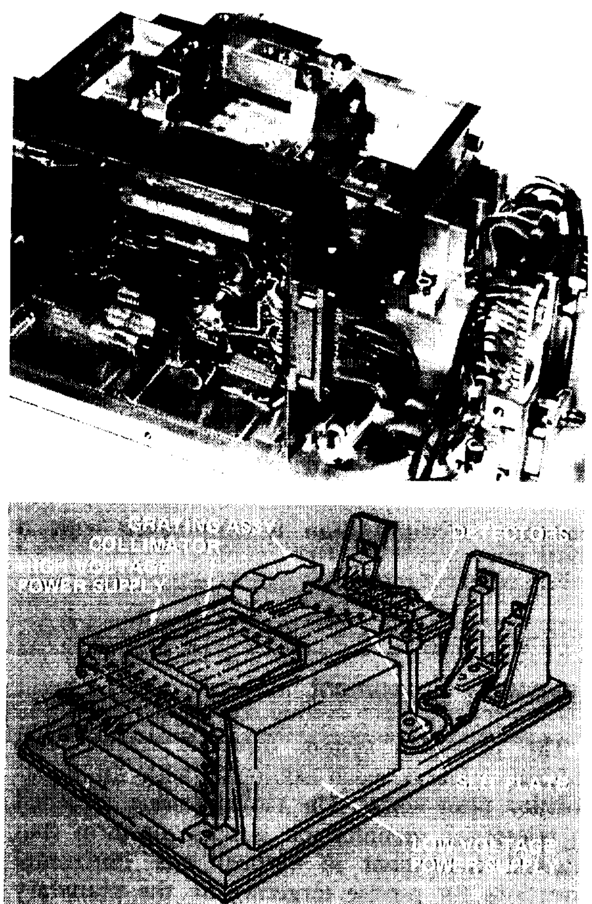
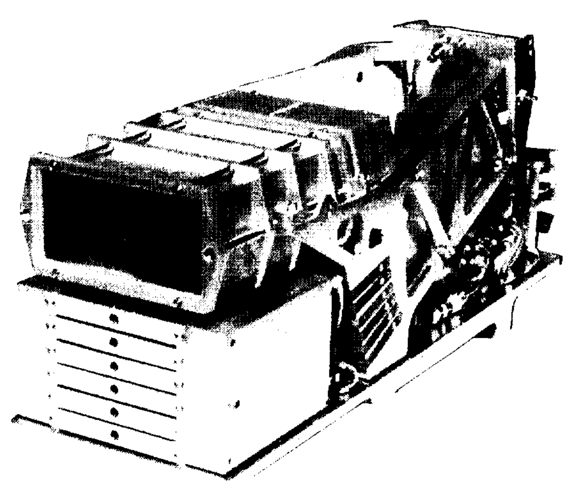
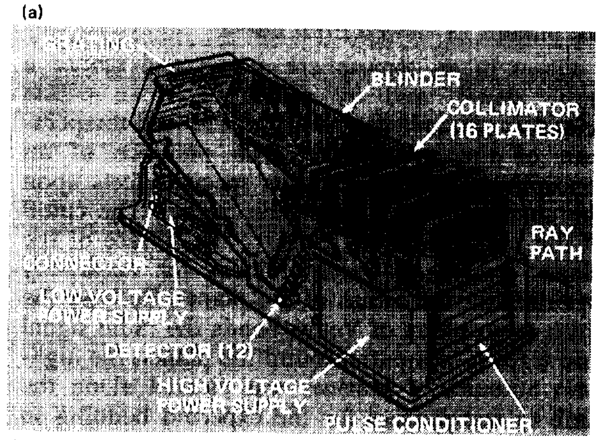


Fig. 3-7. Radiation from the planets in extreme ultraviolet provides information about certain gases such as hydrogen and helium in each planet's atmosphere. An ultraviolet experiment made use of two independent instruments. An occultation spectrometer, shown here, observed the occultation of the Sun by Mercury to probe for a Hermian atmosphere.



(a)



(b)

Fig. 3-8. The second ultraviolet instrument, an airglow experiment, looked for radiation from the planet directly, scanning through the atmosphere on both bright and dark limbs to search for atmospheric gases. Shown here are (a) a photograph of the instrument and (b) a cutaway view.

abundances of the constituents sought in the atmosphere of Mercury, also made important observations at Venus and during the cruise phase between the planets. The angular dimension of the field of view of the airglow instrument was selected to allow resolution to about one scale height of the heaviest expected atmospheric constituent at the limb of the planet (argon), thereby providing data on the structure as well as the composition of the planetary atmosphere.

Celestial Mechanics and Radio Science

These experiments relied upon mathematical analysis of the radio signals coming from the spacecraft, based upon radio tracking of the spacecraft and analysis of the effects of the planetary atmospheres on the radio signal.

In the celestial mechanics experiment the mass and gravitational characteristics of both Mercury and Venus were to be determined from the effect of each planet on the predicted trajectory of the spacecraft. These data would also provide estimates of the internal composition and density of the planets.

The occultation experiment (Fig. 3-9) observed changes to the radio waves from the spacecraft transmitter as they passed through the atmosphere of Venus and Mercury en route to the Earth-based receivers as Mariner passed behind the planets as viewed from Earth.

Gases in an atmosphere refract and scatter a radio signal, and by measuring these effects scientists can calculate the pressure and temperature of the atmosphere. The presence of an ionosphere is revealed by its special effects upon the characteristics of the radio signal. The cutoff of the radio signal as it grazes the surface of the planet provides a measurement for accurately determining the radius of the planet. Because the thick atmosphere of Venus bends the radio signal and traps it in a path around the planet, the high-gain antenna of Mariner was steered along the limb to compensate for the expected bending so as to allow deeper penetration of the radio waves through the atmosphere. The experiment used two frequencies to provide more accurate information about Venus's atmosphere and the interplanetary medium than is obtainable with a single frequency.

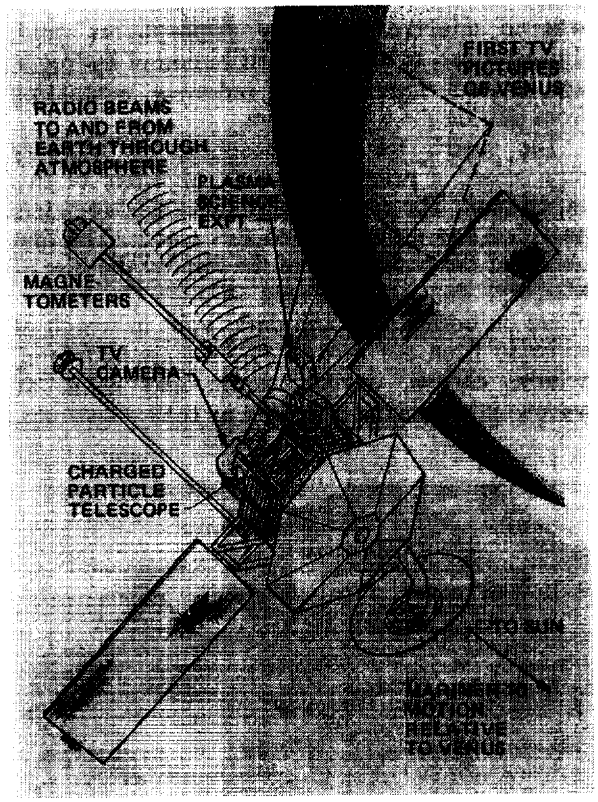


Fig. 3-9. As Mariner passed behind the planet as seen from Earth, its radio waves were interrupted by the bulk of the planet and also by its atmosphere. Changes to the radio waves provided details of the atmosphere and ionosphere of Venus and searched for atmospheric effects on Mercury.

Television Experiment

The television system centered around two vidicon cameras, each equipped with an eight-position filter wheel. The vidicons were attached to telescopes mounted on a scan platform that allowed movement in vertical and horizontal directions for precise targeting on the planetary surfaces. These folded optics (Cassegrain) telescopes were required to provide narrow-angle, high-resolution photography (Fig. 3-10). They were powerful enough for newspaper classified ads to be read from a distance of 400 meters (a quarter of a mile). An auxiliary optical system mounted on each camera allowed the acquisition of a wide-angle, lower-quality image. Changing to the wide-angle photography was done by moving a mirror on the filter wheel to a position in the optical path of the auxiliary system.

In addition to wide-angle capability, the filter wheels included blue bandpass filters, ultraviolet polarizing filters, minus ultraviolet high-pass filters, clear apertures, ultraviolet bandpass filters, defocussing lenses for calibration, and yellow bandpass filters.

A shutter blade controlled the exposure of the 9.8- by 12.3-mm image face of the vidicon for an interval that could be varied from 3 msec to 12 sec. The light image formed on the photosensitive surface of the vidicon produced an electrostatic charge proportional to the relative brightness of points within the image. During vidicon readout, an electron beam scanned the back side of the vidicon and neutralized part of the charge so as to produce electric current variations proportional to the point charge being scanned at the time.

These analog signals produced from the vidicon readout process were electronically digitized as 832 discrete dots or picture elements (pixels) per scan line, and presented to the flight data system in the form of 8-bit elements for transmission. Each TV frame—one picture—consisted of 700 of these vidicon scan lines. All timing and control signals, such as frame start, line start/stop, frame erase, shutter open/close, and filter wheel step, were provided by the systems on board the spacecraft.

The television experiment had the objectives of providing data to permit the following scientific studies of Mercury: gross physiography, radius and shape of the planet, morphology of local features, rotation and cartography, photometric properties, and regional color differences. For Venus the experiment aimed at obtaining data on the visual cloud structure, scale and stratification, and the ultraviolet markings and their structure and motions. The television experiment also searched for satellites of Mercury and Venus and was used for targets of opportunity such as Comet Kohoutek.

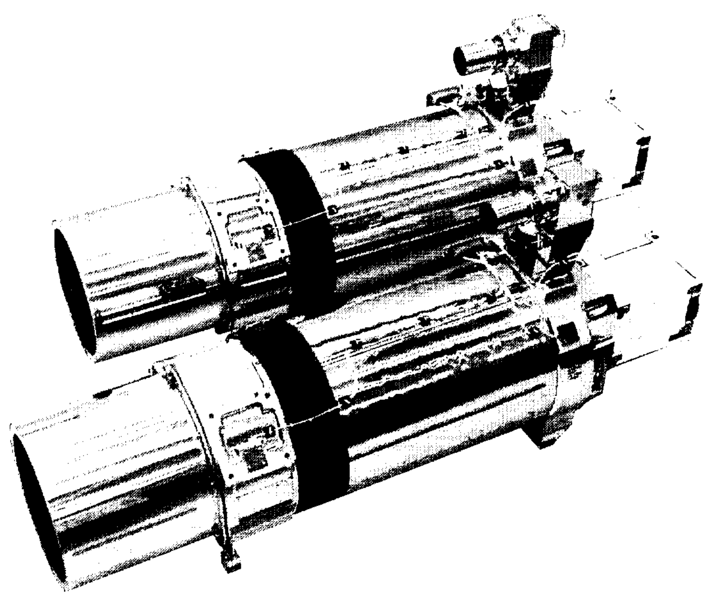


Fig. 3-10. The imaging experiment relied upon twin Cassegrain telescopes to focus magnified images of the planets on vidicons. This provided high-resolution imaging of the planetary clouds and surfaces.

Chapter 4

Spacecraft, Scientists, and Schedules

A 1.5-HOUR LAUNCH WINDOW on November 2, 1973 (November 3, on the East Coast), provided the best science data return possibility for the mission. Although there were opportunities in other years, the 1973 opportunity offered one of the lowest launch energies to swing by Venus and subsequently encounter Mercury. When the project was formally initiated in December 1969, four years were available to plan and implement this complex new interplanetary mission: the first use of gravity-assist and the first two-planet mission to be undertaken by the National Aeronautics and Space Administration.

Not only was the mission under tight cost constraints that demanded use of new management philosophies, but also some significant changes had to be made to the earlier Mariner spacecraft to meet the special requirements of the Venus-Mercury mission.

Scientists, too, were constrained in their experiments—the rule was to achieve maximum science for minimum new development. Since there were options on the flyby path at Mercury encounter, conflicts in the demands of scientists arose from science opportunities offered by these different modes. The mode finally selected, passage on the night side, provided good conditions for nonimaging science return but was the worst situation for imaging science. To meet these constraints the TV imaging system had to be redesigned, and there were demands for real-time return of data at satisfactory error rates. For example, while detailed analysis had shown that TV imaging could accept relatively high rates of bit errors (about 1 in 50) and still produce high-resolution pictures of suitable quality, the other science experiments had to be assured of very low bit error rates (about 1 in 10,000). To constrain the TV system to such low bit error rates would have considerably reduced the number of TV images and made it impossible to produce a full-disc, high-resolution mosaic of Mercury during the short period available for TV imaging during the night-side pass. The solution to this conflict was the implementation of a two-channel, independently commandable data stream, using a new form of carrier modulation devised for this purpose by JPL's telecommunications engineers.

Several activities connected with the design of the spacecraft produced conflicts of requirements to meet the objectives of the mission. Quick and satisfactory resolution of these conflicts was a continuing challenge to the management of the program, which had to meet the tight schedule and yet still keep costs within the budget limitations.

Upgraded Spacecraft Capability

A decision to increase the size of the nitrogen gas tank, thereby increasing the amount of reaction control gas from the 2.45 kg (5.4 lb) used by Mariner Mars 1971 to 3.62 kg (8.0 lb) for Mariner Venus/Mercury was made early, principally to accommodate predicted worst-case effects of solar pressure on the appendages and to allow for total depletion of one of the redundant halves of the gas system by a valve failure early in the mission. Without this change, there would not have been sufficient reaction control gas—a margin of 0.91 kg (2 lb) was provided—to allow the extended mission, which added so much to the science coverage at Mercury by three encounters with the planet.

Originally the spacecraft was to be capable of a maneuvering velocity change of 56 m/sec (184 ft/sec). By using an improved propulsion unit, incorporating a larger tank used on the Pioneer 10 and 11 spacecraft, the final capability of the spacecraft was more than doubled, to 122 m/sec (401 ft/sec). Again, this made possible the multiple encounters with Mercury.

The solar panels, originally specified as being of a fixed tilt of 60 deg, were, in the final spacecraft design, capable of an independent variable tilt, from 0 to 76 deg, on command from the ground. This capability was eventually used for "solar sailing" which, as it turned out, made the extended mission possible when trouble developed in the gyro system. The original two-position, low-gain antenna was upgraded to provide three positions on command, allowing communication with Earth following first encounter. Moreover, the final articulation pointing system of Mariner Venus/Mercury was much improved over the original scan system based on the Mariner Mars 1971 design. High-gain antenna articulation was increased from one to two degrees of freedom to permit transmitting to Earth at all times instead of just at Venus and the first Mercury encounter. All elements controlled by the subsystem—the scan platform, high-gain antenna, and solar panels—could be pointed to within 0.35 deg and their positions reported back to the flight data system for telemetry to Earth within 0.1 deg in the position mode. In the incremental mode the subsystem positioned the scan platform within 0.075 deg.

Sail vs V-Tilt Solar Panels

On Mariner spacecraft the thousands of solar cells that convert sunlight into electrical energy were mounted on the face of flat rectangular panels extending like wings from the spacecraft. Since the new spacecraft had to travel from the orbit of the Earth to that of Mercury, its solar cell energy-gathering system had to accommodate to the change of nearly 5 times in the amount of solar radiation that would be received. Early studies by JPL and Boeing concluded that the best way to keep the solar panels at the right temperature of about 100°C (212°F), while still providing a fairly constant power output from them into the spacecraft electrical system and also meeting the weight constraints, would be to

Fig. 4-1. One method of safeguarding the solar panels from overheating as Mariner approached closer to the Sun was to tilt them into a V-configuration.

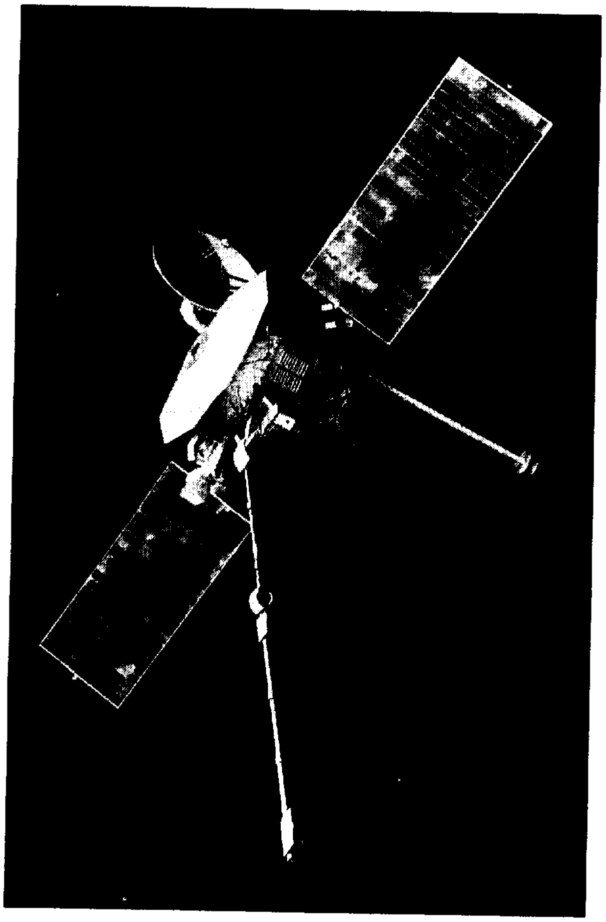


Fig. 4-2. Alternatively, they could be rotated away from the Sun along the long axis. This was the method chosen because it allowed nitrogen gas thrusters to be mounted at the tips of the panels, thus attaining more efficiency in orienting the spacecraft.

articulate or tilt the solar panels as the spacecraft approached the Sun. Furthermore, after considering two ways of tilting the panels, a V-tilt was chosen (Fig. 4-1). However, as the project developed, it was discovered that V-tilt might lead to unacceptable thermal input to the bus and the instruments mounted on the platform, so a study was started to compare V-tilt and rotatable ("sail") configuration.

The study concluded that even though the structures and mechanisms needed for a sail configuration (Fig. 4-2) were more complicated, weighed more, and would cost more than those for a V-tilt, scan platform temperature control would be simpler, and the solar panel temperatures would also be lower at high angles of tilt. In addition, this design permitted the mounting of the roll/yaw cold gas jets at the ends of the sails, providing added leverage for their thrust. Accordingly, the sail configuration was recommended by Boeing in August 1971, and was accepted by Project management at JPL.

Protecting the Rocket Engine From the Sun

Another problem arising from the close approach to the Sun was protecting the maneuvering rocket engine from direct solar radiation and preventing the conduction of solar heat from the engine into the octagonal equipment compartment. Earlier studies had concluded that the preferred direction of the rocket nozzle should be toward the Sun during the cruise phase of Mariner operations.

The basic configuration proposed by Boeing at the time of contract award made use of a thermal door over the rocket nozzle to minimize the effects of solar radiation. But this door imposed a reliability problem if it should fail in either an open or a closed position. If the door remained open it would allow the propulsion subsystem to overheat. If, on the other hand, the door failed to open and remained closed it would be blown off the first time the engine fired. Again the spacecraft would be unprotected and would have to survive the resultant solar heating. Since in both failure modes spacecraft survival without the door would be necessary, engineers took a new look at the true effectiveness of the rocket engine door to ascertain whether or not it could be eliminated from the spacecraft design.

The main parts of the propulsion system that had to be safeguarded from solar overheating were the propellant tank, the valve that controlled the flow of propellant to the rocket thrust chamber, and the thrust vector control actuator. Engineers at Boeing used a computer thermal model of the propulsion unit and found that with suitable modifications the engine could survive solar heating without a door.

The modified design ensured that radiation entering the sunward-facing nozzle would be radiated into space from the thrust plate and from the inner surface of the nozzle. The plan was that surfaces of the thrust plate and the thrust vector control actuator would be coated with a paint that emitted heat readily, while the outer nozzle surface and the inner surface of the thrust vector control actuator support were polished to reflect radiant heat from the inner nozzle. Finally, the propellant tanks and lines were protected by multiple layers of insulation.

Although the engineering analysis indicated that it was theoretically safe to eliminate the door, engineers decided that the consequences of such a decision were so far-reaching that a practical test had to be made. Accordingly, high priority was given to a verification test in which actual materials were tried out under simulated conditions. The theoretical analysis was vindicated, and the tests confirmed that the engine thermal door with its attendant problems of reliability could be eliminated from the flight spacecraft.

Further Protection From the Sun

In addition to solar panels and propulsion system, many other components of the spacecraft needed protection from solar radiation. At the beginning of the program, considerable doubt existed that Kapton, a commonly employed heat-protection material, would survive in the anticipated environment. Kapton had been suggested as a replacement to the Teflon used on earlier Mariner spacecraft when engineering tests showed that Teflon failed at the intensities of solar radiation expected at Mercury. However, Kapton was found to become brittle with long exposure to temperatures above 354°C (670°F) and also in the environment of ultraviolet light and protons expected sunward of Earth's orbit.

The scientists at Boeing quickly subjected several alternative materials to exhaustive tests at the Boeing Radiation Effects Laboratory. But it was discovered that the tests were inconclusive because of contamination of the material by an unidentified substance and because the flux of protons was not large enough to simulate the flux at the distance of Mercury. There was no time to conduct a further test series, so a working group of materials experts from JPL and Boeing sought acceptable alternatives to Kapton. After much investigation and long working hours the group was able to recommend that several alternatives were indeed available: stainless steel cloth backed by aluminized Kapton; metallic foil of titanium, stainless steel, or aluminum; Teflon-coated glass fiber cloth, known as beta cloth, aluminized on one side and backed by aluminized Kapton; clear-anodized polished aluminum, known as Alzak; and optical solar reflectors. Project management selected the beta cloth and the clear-anodized aluminum for more detailed study.

Fig. 4-3. The flight sunshade proved effective in protecting the spacecraft from solar heating generally.

Checks were made to see if the outgasing from the beta cloth and its subsequent loss of weight resulted in deposits on neighboring surfaces and what, if any, changes took place to the cloth, such as discoloration and reaction with other spacecraft materials. The results were that Teflon-coated glass cloth could be expected to survive the environment at Mercury encounter. Analysis of the beta cloth suitability for the sunshade showed that even if the cloth discolored and turned black, the sunshade would still function adequately.

The working group therefore selected a foldable beta cloth sunshade and suggested that all sunlit thermal blankets used on the spacecraft should have an outer layer of beta cloth also.

Two flight sunshades and a backup unit (Fig. 4-3) were therefore designed and fabricated. The use of foldable designs resulted in the project's being able to make good use of existing hardware that had demonstrated reliability for deploying sunshades in space, but because of the increased weight of the beta cloth, some modifications were needed to strengthen deployment springs and the deployment assembly generally.

Making Sure the Spacecraft Obeyed Commands

Whereas future interplanetary spacecraft will have a redundant central computer and sequencer that provides alternative paths, Mariner Venus/Mercury had only one computer and sequencer. A backup command capability had to be provided through the flight command unit that would not leave the articulation and pointing system susceptible to command errors. This system pointed the high-gain antenna and controlled the scan control subsystem for directing both the TV and ultraviolet instruments at the target planet. The impact of an incorrect command on the scan platform was unacceptable since it would take too long to detect back on Earth and issue a correcting command.

After considerable debate and test activity on different designs, it was decided to use both a position mode and an incremental mode design. Thus an initial position in a typical scan sequence would be commanded by position commands, and then the following frames of a photomosaic would be acquired by incremental updates. These joint modes obviated problems of storage of sufficient position commands for a complete mosaic sequence, while at the same time they ensured that should a command be in error the scan platform would be returned to a correct position for a subsequent sequence with loss of only part of the encounter sequence, and not all of it. Also, most important, the incremental command mode was required to allow fine stepping with sufficient picture-to-picture and slit-to-slit precision for mosaicking and proper UV scanning.

Fine Tuning for Encounter

Once the spacecraft was placed on a trajectory to Venus, and when this trajectory had been accurately determined by tracking, controllers had to fine-tune the trajectory to get a more precise Venus encounter that would lead to the minimum use of propellant to fly by Mercury at the correct time, distance, and orbital inclination. Such trajectory correction maneuvers (four were planned but only three were actually needed during the flight to the two planets, five more for the subsequent returns to Mercury) relied upon the spacecraft's being oriented accurately in space by command and then provided with a given thrust for a known period of time in a definite direction. The spacecraft carried a main propulsion system for this purpose.

The Mariner Venus/Mercury main propulsion system was a modified Mariner Mars 1969 design, but by the spring of 1971 additional velocity change requirements were imposed on this propulsion system by mission planners. More propellant had to be carried aboard the spacecraft, and a larger storage tank was needed. The one used on Pioneer 10 and 11 was chosen. By 1973, Boeing, which contracted with JPL to produce the new propellant subsystem, had delivered a subsystem mockup and, just over a month later, a development test model of the new subsystem. The choice of a "blowdown" design, wherein the driving gas pressure on the propellant is allowed to diminish from firing to firing, was a major departure from earlier Mariners and represented a first for this class of spacecraft. Another change was made later when the Skylab program experienced difficulties with thrusters, which had oxidizer valves and valve inlet fittings identical to those on Mariner Venus/Mercury. The time was August 1973, only three months before scheduled launch of Mariner. Propulsion engineers reworked the subsystem and replaced valve inlet fittings. Propellant loading was completed with only six days left before the scheduled time for installation in the spacecraft.

Test, Test, and Test Again

Interplanetary spacecraft must be reliable. Once the spacecraft has been launched into space, a failure cannot be repaired. The spacecraft must either carry a redundant part to replace a failed part, or controllers must devise ways to complete the mission by working around the failed part. Because many parts of a spacecraft are critical—their failure could be catastrophic—the whole process of designing and building and launching a spacecraft is accompanied by test upon test upon test.

For example, the high-gain antenna required considerable development to meet the performance requirements of Mariner Venus/Mercury, especially for the distant Mercury encounter. Every microwatt of transmitted power was required at Mercury to get the many pictures back to Earth during the short period of the encounter. When a new combined S- and X-band feed was installed on the antenna dish it was found that the expected gain from the antenna was below that required for the 1220-mm (48-in.) diameter antenna. After considerable effort to increase the gain, the decision had to be made to increase the diameter of the reflector to 1370 mm (54 in.) to obtain the required effective radiated power.

Similarly, development testing of the articulation and pointing system took place during July and August of 1972 to confirm that the backlash and stiffness of each movable unit were acceptable, to make sure that sufficient reserve of power was available to move the various actuators, and to check on the positional accuracy with which the scan platforms could be moved. Checks were also made to ascertain that these various movable elements could be unlatched from their stowed position and would reliably lock up in their operating positions.

During these tests some problems were encountered in locking up the dish of the high-gain antenna, resulting in the requirement that the lockup pin be changed. Later, these same development tests (Fig. 4-4) were repeated on the two flight spacecraft, and all functions were found to be satisfactory.

A most critical item to the success of the mission was the solar panel system, since if these panels did not move from the stowed to the operating position, the spacecraft would be starved of electrical energy and could not operate. Viscous boost dampers had to be developed for the solar panels as well as for the magnetometer boom to prevent the two systems from banging together during the launch. The objectives of this development program were to verify that the damping force would meet the requirements for the spacecraft over the operational range of vibration frequencies, and to develop assembly techniques for the magnetometer boom damper. During the development program, both dampers were subjected to small- and large-amplitude vibration testing at many frequencies. These tests were successful and showed that the dampers would safeguard the solar panels and the magnetometer boom.

A development test fixture was used to verify that the release mechanism exerted sufficient force to unlatch the solar panels and the other deployable structures and that there were adequate forces to move all these systems into flight position at the required rate. The test fixture was also used to test the structural strength of the solar panels and other assemblies to make sure that they would be capable of withstanding the

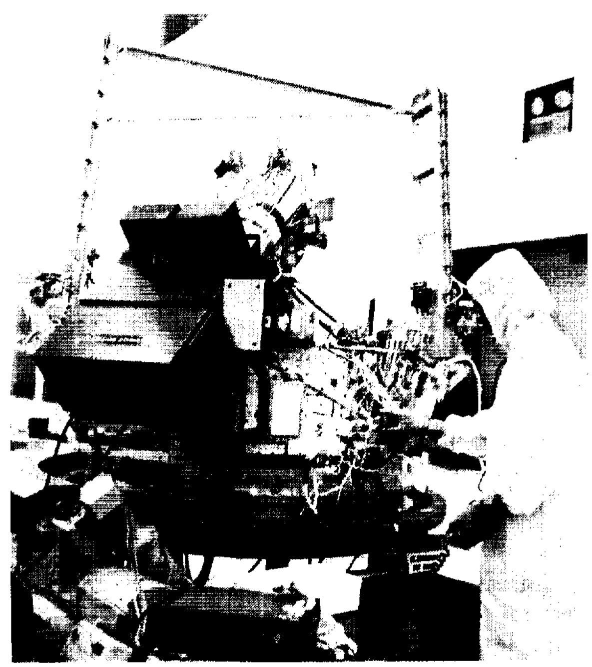


Fig. 4-4. Many development tests were performed on the spacecraft to ensure that it would meet all performance specifications

forces exerted during launch. Reliable operation was demonstrated after several modifications had been completed. Since the appendages mounted on booms had to deploy in the weightless or zero-g condition of flight through space, other tests were performed to simulate the zero-g condition. As a result of these tests it was necessary to reduce the rate at which the low-gain antenna deployed, to modify the high-gain antenna's latching mechanism by adding a kickoff spring to the boom release, and to develop a special tool for the assembly of the restraint mechanism for the plasma science experiment.

As the program progressed, extensive testing took place with the developmental test model of the spacecraft, which was subjected to high- and low-frequency vibrations and to acoustical inputs ("noise") of various frequencies (Fig. 4-5). All the structures and mechanisms tested were either flight hardware or flightlike hardware, except for the high-gain antenna reflector and some other minor components which were simulated. Thus it was shown that the spacecraft and all its subsystems could withstand the vibrational stresses of the large rocket engines of the launch vehicle. Test results agreed closely with the calculated effects of vibration. No failures or excessive deformations were observed during any development test model vibration testing, nor during the test firing of pyrotechnic charges on

Fig. 4-5. The spacecraft was also vibration-tested to make sure that it could survive the stress of launching by the big rocket booster.

the spacecraft to release structures from launch stowage to the cruise positions. The subsystems of the Mariner Venus/Mercury spacecraft had been certified with a clean bill of health to ride in the launch vehicle to interplanetary speeds.

The spacecraft was also tested rigorously to determine its ability to survive the thermal stress of the inner Solar System (Fig. 4-6), the degradation of external surfaces by the environment of space, and hot-firing of the rocket engine. The high-gain antenna was also tested for its ability to perform when exposed to the intensity of nearly five suns' radiation (Fig. 4-7).

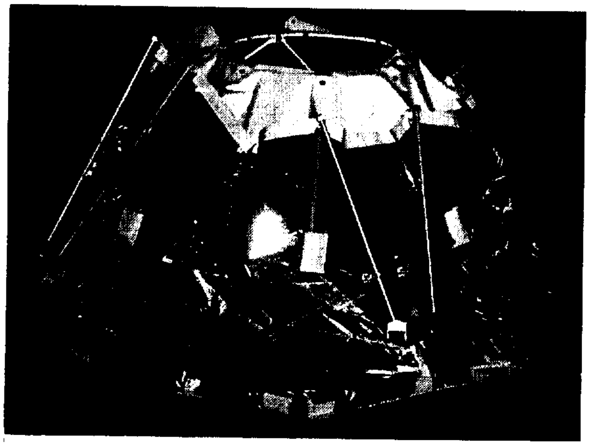
Successful deployment of the sunshade was critical to the success of the mission to Mercury. If it failed to open and shield the spacecraft, the intense solar heat would damage the electronic and scientific equipment. To establish confidence in the concept used for deployment of the sunshade, a development test (Fig. 4-8) faced the sunshade upward and downward to deploy both against and with the force of gravity. The sunshade's deployment was also tested with broken lanyards, nonsymmetrical solar panel deployment, and broken deployment springs. The sunshade passed all these tests, showing that it would deploy under the most severe conditions of a combination of possible failures.

The final series of tests began when the flight spacecraft was subjected to rigorous solar thermal vacuum conditions in the space simulator at JPL (Fig. 4-9), where testing simulated the harsh solar environment that the spacecraft must expect as it speeds into the inner Solar System. The spacecraft was again tested to make sure that its performance met all specifications, followed by further tests to ensure that it was compatible with the Deep Space Network and the Mission Operations System. These tests at JPL occupied most of July 1973, and the spacecraft came through them with flying colors. There were, as expected, some minor glitches and some differences in the actual temperature experienced at equivalents of 1, 2, and 4.8 suns, but these were within tolerances, and the spacecraft was considered ready for launch.

Meanwhile, at the Eastern Test Range, the backup spacecraft had arrived from Boeing on August 4 and went through a series of tests to verify the adequacy of the test procedures and all the spacecraft-related equipment that would later be needed for the flight spacecraft on its arrival at the range.

Fig. 4-6. It was also put through rigorous thermal stress tests in a simulator at the Boeing plant.

Fig. 4-7. The high-gain antenna was tested in a simulator to check whether or not it could withstand the heat of 4.8 suns: the intensity it might have to withstand at Mercury.



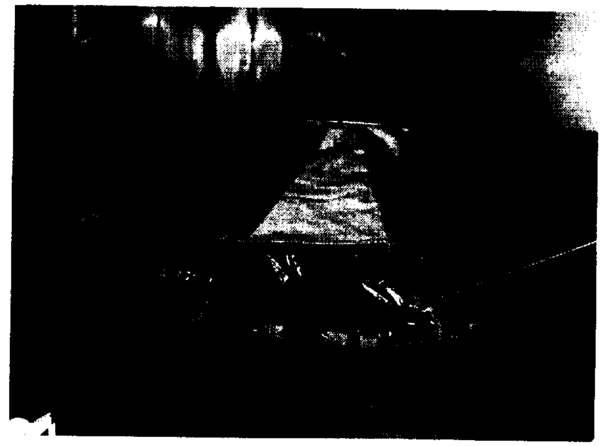


Fig. 4-8. Tests are made to find out if the sunshade will deploy when the spacecraft emerges into space. The sunshade had to be folded up for the launching.

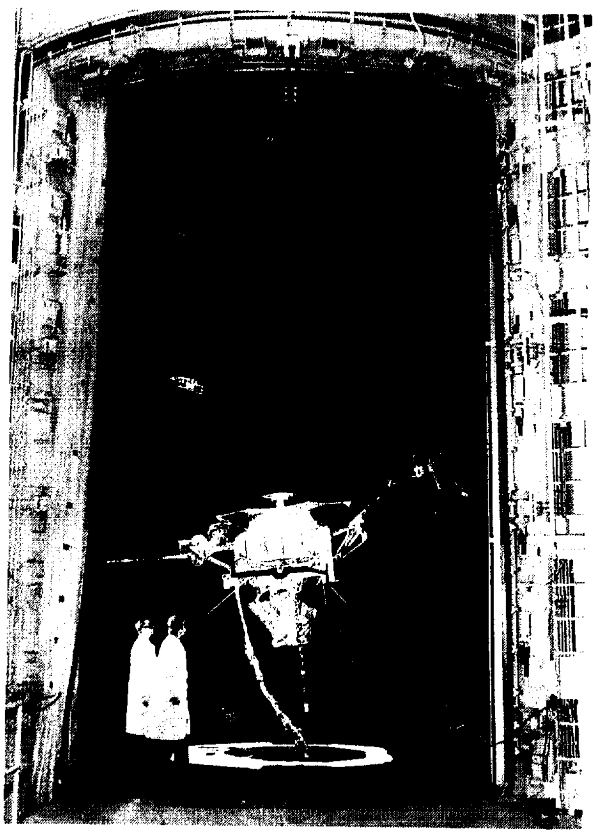


Fig. 4-9. Final space simulation tests took place at JPL, where the spacecraft went through a series of exercises under conditions of vacuum and solar radiation it was expected to experience in Mercury orbit.

Problems Overcome

As with most complex technical programs, many problems beset the engineers and scientists as they developed the new spacecraft. And, as always, the challenge was to identify and resolve the problem as quickly and as inexpensively as possible.

Once, for example, during testing at the Boeing facility, the radio frequency subsystem lost uplink lock while operating near threshold. Another similar unit lost lock while operating during solar vacuum testing in the test chamber at JPL. Both units had to be returned to the subcontractor, where the trouble was corrected by the installation of a filter in the wiring.

Another problem was identified early during evaluation tests of the data storage subsystem. The tape transport failed to start consistently from the left-hand end of the tape-parking window, and engineers thought that this might be due to wear that was caused by low humidity of the magnetic tape itself. To overcome the difficulty, the unit was preconditioned prior to shipment to the launch site. A humidified mixture of argon and helium was used within the tape transport while the tape was being run continuously. The final relative humidity of both the magnetic tape and the internal atmosphere of the tape transport was established at the required level. Actual usage of the system in flight exceeded that proposed before the flight. Mission playback of both high- and low-rate recorded data was very good, with low bit error rates.

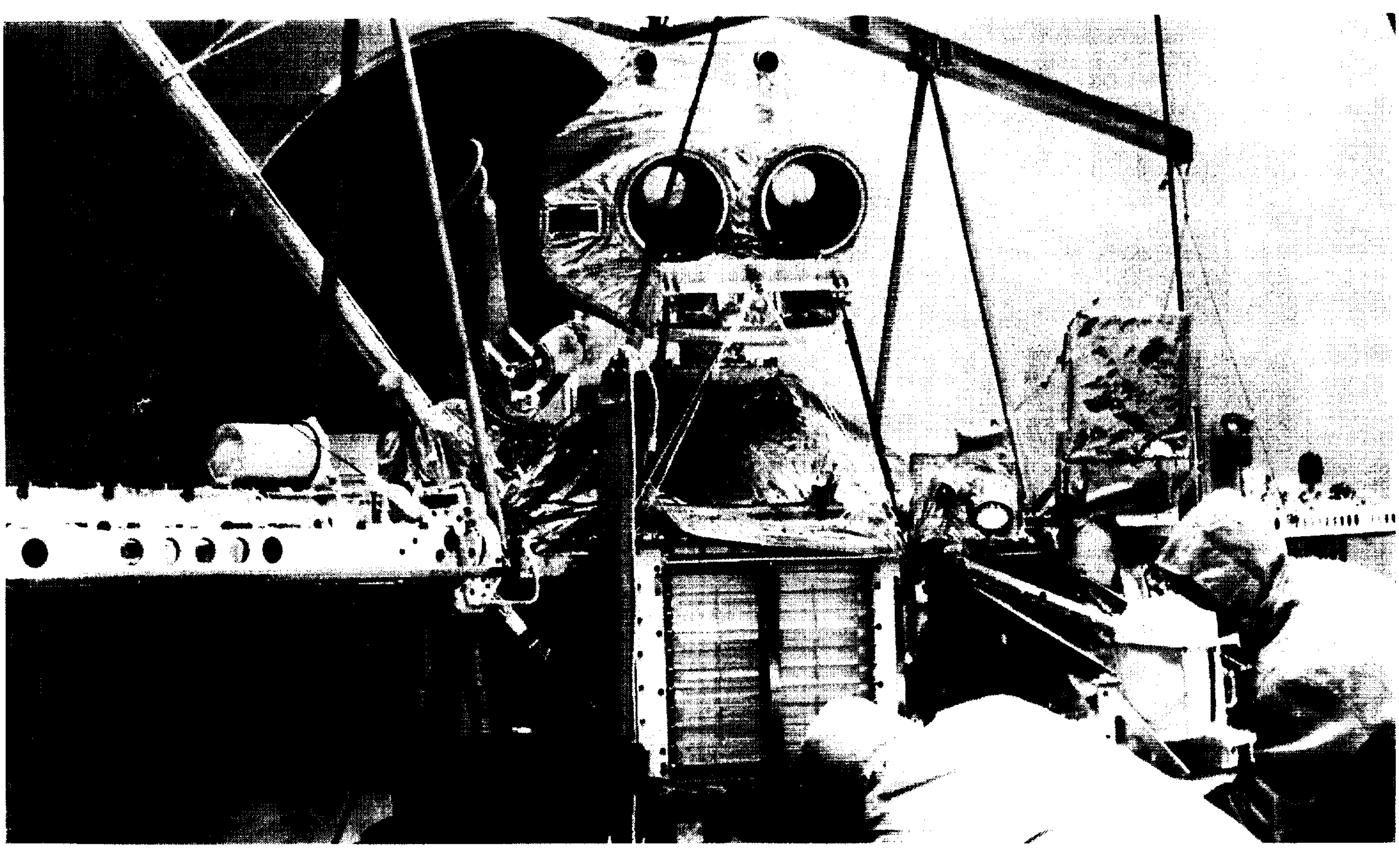
In December of 1972, the spacecraft battery was accidently connected to the attitude control electronics and several electronic modules and harnesses were damaged. Not only had the damaged modules to be replaced but nearby components had to be checked thoroughly to make sure that they, too, had not suffered stress from the accident. Further tests called for replacement of more modules, and the rebuilding caused a delay in the spacecraft systems test which could only be regained by a specially devised "catchup" test in which the attitude control electronics were powered-up continuously for several days and all the functions of the subsystem were exercised faster than normally. In this way the tight schedule for delivery of the spacecraft to meet the launch window was not affected.

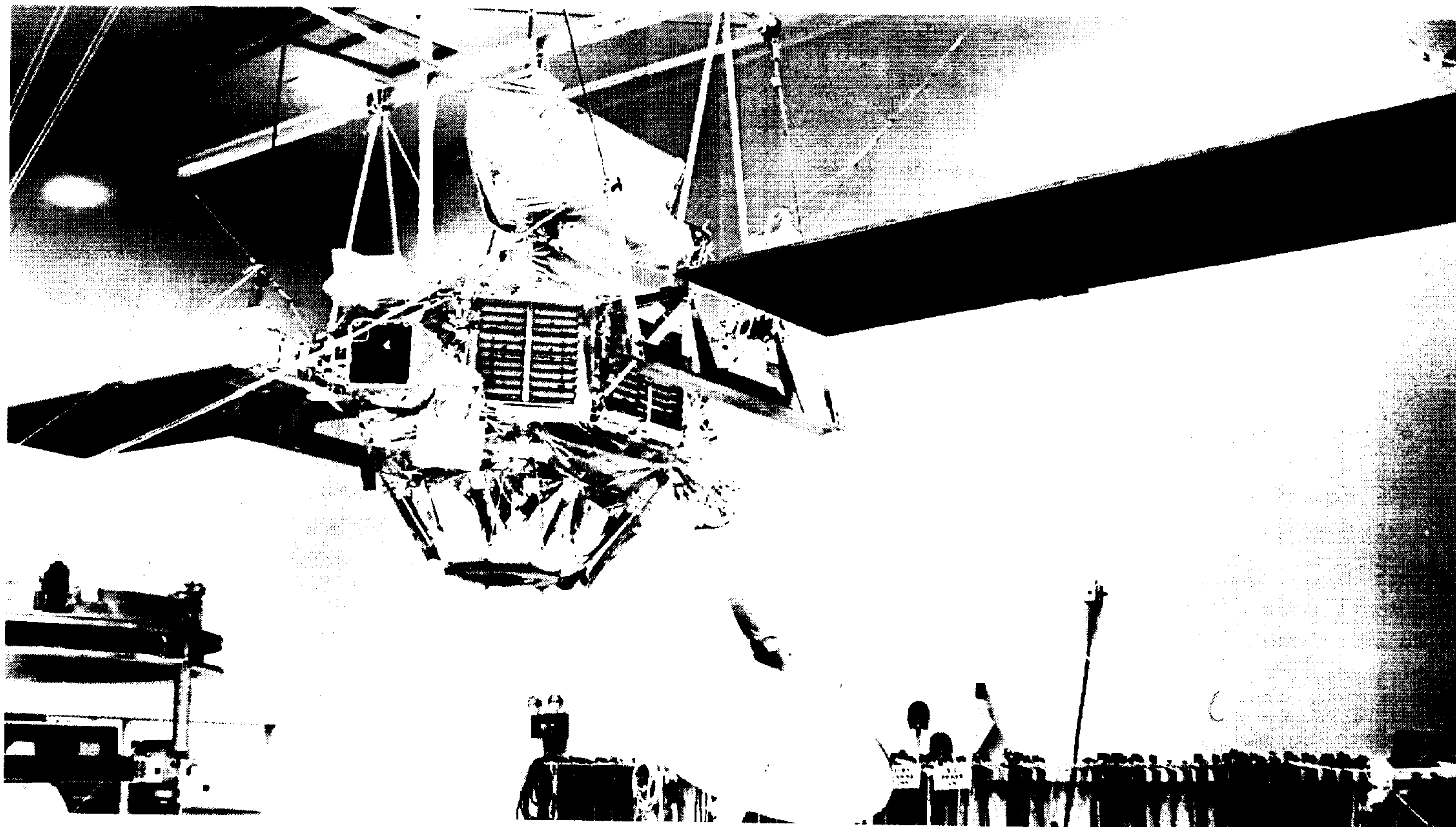
During design and development of the magnetometer boom, it was discovered that intrinsic frequency characteristics would likely interact adversely with the spacecraft during maneuvers, causing dangerous vibrations. As a result, the engineering group at Goddard Space Flight Center had to redesign the sensor canisters, brackets and cable supports. The weight reduction shifted the characteristic frequency away from the dangerous region. Subsequent testing during the summer of 1974 at the Boeing Company's facility called for the zero-gravity environment to be simulated. A special compensation string and support was developed for this. Unfortunately, during one of the deployment tests, the string broke and the boom was dropped. A critical interface bracket and inboard hinge of the two-section boom was damaged. A rather frantic rebuilding effort had to take place at Goddard Space Flight Center to provide another qualified and tested boom for flight. Much weekend and overtime work was demanded and trips to international scientific meetings in August and September had to be cancelled for the principal investigator but the deadline was met.

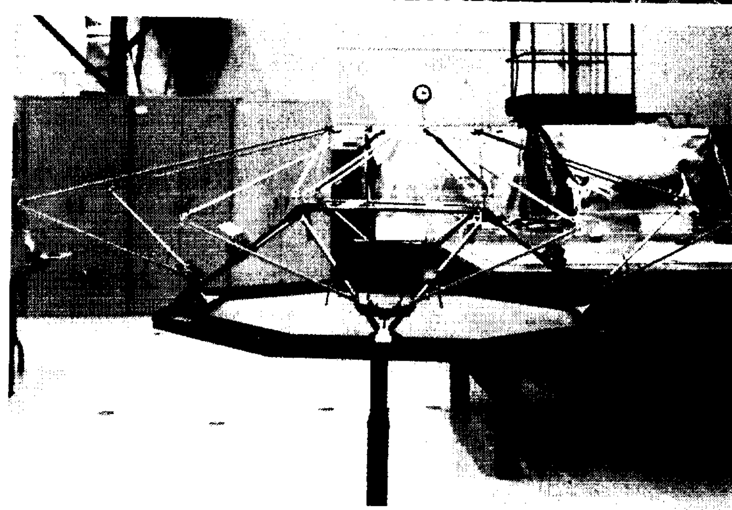
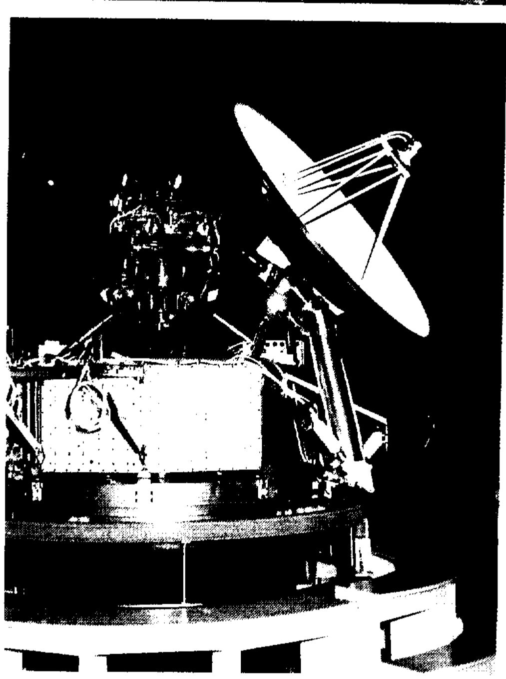
Meeting the Milestones

It is a long hard road (Fig. 4-10) from contract award in response to a written proposal to the shipment of a finished spacecraft to mate with its launch vehicle at the Kennedy Space Center,

Fig. 4-10. Manufacturing of an interplanetary spacecraft calls for minute attention to detail, scrupulous cleanliness, and a seemingly endless test program—all in a tight schedule aimed at meeting the launch window on time.






Florida. It is a road punctuated by milestone events which must be reached at certain times in order to meet the launch window, predetermined by the inexorable movements of planets in their orbits.

The planets will not wait on human failure. Men have to work and produce and be ready with their space machines on time, or the whole effort is in vain and the opportunity for an interplanetary mission is lost. Often the opportunity is not repeated for decades, sometimes centuries. A special breed of men and a special type of human endeavor are required to meet the requirements of space missions.

Management of a planetary mission requires the discipline of control of each major effort in the program. It must define accurately the events, activities, and resources necessary to reach objectives on time and within budgets. Responsibility for all tasks has to be clearly defined.

Major milestones in a program master schedule provide key dates from which detailed schedules for work units are derived. With Mariner Venus/Mercury, many formal progress reviews took place, keyed to program events that earlier had been identified as major indicators of progress significant in previous planetary efforts. Free communications on program matters speeded management decisions when corrective actions were needed to keep the program on schedule.

Considerable emphasis was placed on early identification and reporting of problems. Special technical sessions followed each regular monthly program review and identified problems needing solutions. In June 1972, Boeing instituted a weekly log prepared by the work unit personnel in each area of activity and summarized in a weekly problem report. When the test phase of the program was reached, daily meetings were held with test and operations people. But in all this activity the basic premise was that the success of the project depended upon men and women, not upon management systems. Dedicated people were supported by good communications to top management.

Science Coordination

Following selection of the experiments to be flown on Mariner Venus/Mercury, the Project Science Steering Group, consisting of principal investigators and science team leaders, was constituted. The emphasis of the Science Steering Group was upon interaction of the scientists with the project. One example was the design of the telemetry system with regard to the allocation of the rate at which information would be transmitted from spacecraft to Earth. In negotiating with the experimenters early during the project, the scientific experiments and their interfaces with the spacecraft flight data subsystem were discussed.

In one meeting of the Science Steering Group at JPL, the principal investigators got together with the project staff and allocated the two planned bit rates of 2450 and 490 among the various experiments. This was the time at which the need for a lower bit rate was identified because the higher rate could not be accommodated during the extended mission on the 26-m (85-ft) antenna net. The range of rates needed was from 1050 bits/sec for magnetometer experiments to only 33 bits/sec for the infrared radiometer. There were some conflicting requirements aired at the meeting, but these were all resolved through mutual understandings and discussions.

Another example was the quick recognition that not only did bit rates differ for the different experiments but also the quality of data needed for the TV experiment was quite different from the nonimaging science. Whereas the latter could accept only very low bit rate errors, the photo scientists could obtain images of usable quality at high bit error rates, thereby obtaining more pictures at higher transmission rates.

The imaging experimenters also needed the flight data system to have the capability to command a quick change from high to low transmission rates or vice versa depending on inspection of the quality of the incoming pictures in real-time. The result was that it was decided to decouple the imaging science data from the nonimaging science data by the use of separate high and low data rate channels. Dr. Stan Butman at JPL designed a special modulation scheme, termed interplex modulation, which permitted decoupling of two data transmission rates. The allocation of power in two subcarriers was changed so that a cross modulation channel could be used to carry the lower data rate subcarrier.

Another major interaction between scientists and engineers was in regard to the placement of instruments on the spacecraft to provide suitable fields of view necessary for the science experiments. Several months after the start of spacecraft design at Boeing, the locations of all instruments were changed in order to better satisfy requirements of scientists for the fields of view of their instruments. The Canopus tracker's 30-deg offset resulted from this rearrangement.

Thus, in the early phases of spacecraft design, there was much interaction among JPL divisions and project staff, the Boeing Company, and the principal investigators, separately and as a science group—this interaction being aimed toward designing a spacecraft that would really do the exploratory job assigned to it and do the job well. Costs of the science experiments were also rigorously controlled.

There was a very strong interaction between the project and the principal investigators in defining the data records and detailed planning on how these records would be obtained during the mission. Originally, it was planned to use the real-time data from the stations and to generate the master data record from this real-time data and a log tape called the system data record. When this plan was examined more closely with the principal investigators, it was ascertained that the amount of data recovery would, from a percentage point of view, be very high: on the order of 95%. But with the help of people who had done systems analysis of data returned from the Pioneer 10 spacecraft to Jupiter, it was found that the way in which the errors were distributed in the real-time link was such that there would be uninterrupted error-free data for brief periods of only a few minutes. At other times, the data would contain errors. So the design of the data system was completely changed—the original data record as recorded at the DSN station was to be flown to JPL and merged with the system data record obtained in real-time over the ground data links to produce a relatively error-free master data record from which the scientific data would be supplied to the experimenters. During the encounters, these error-free data were available to the investigators within a few hours. During the cruise mode, where time was not so important, the data were made available within 1 to 2 weeks.

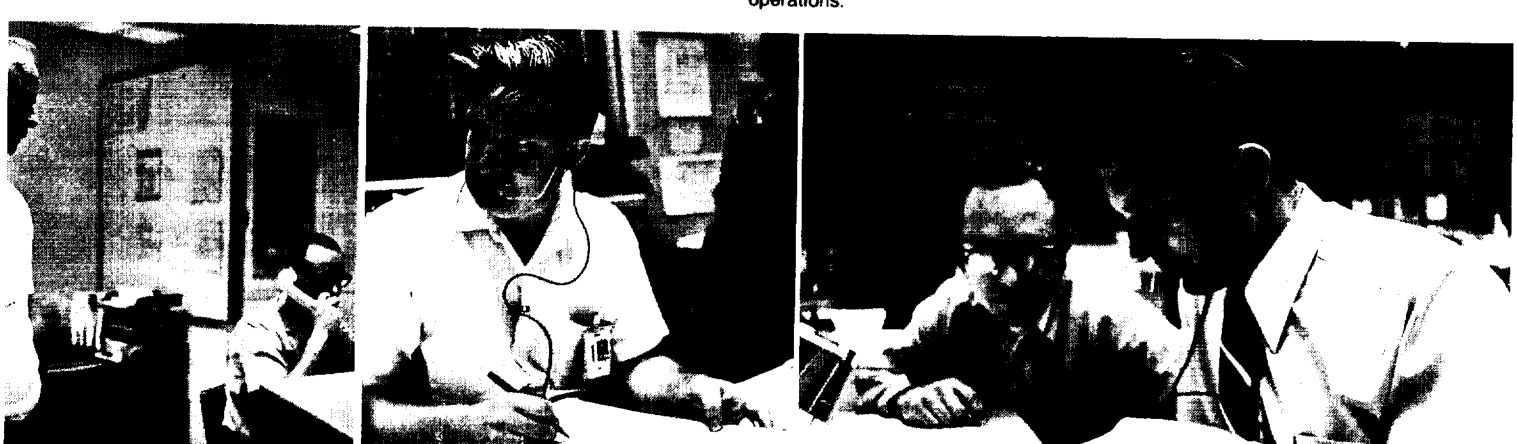
All principal investigators met the schedules for delivery of their science instruments, although there were some anxious times. A low-energy telescope was added to the particle experiment to extend the lower bound of charged particle measurements and to permit low-energy protons to be detected in the presence of low-energy electrons. Changes were made to the plasma science experiment, which originally proposed a body-fixed triaxial detector to look in an antisolar direction. This instrument was deleted at the time of selection to reduce cost. Later, at the suggestion of the plasma experimenter, a single-axis instrument was added to the scan package at no additional cost. This was fortunate because the main instrument on the scanning platform failed because of a stuck protective door, and the only plasma data were obtained with the add-on unit.

A third addition following initial selection of science instruments was the wide-angle filter that was added to the television optics in order to allow the search for structure in Venus's visible clouds. The path by Venus was from the planet's dark side, so the only good phase angle views between spacecraft, planet, and Sun suitable for cloud analysis would be around closest approach. But at closest approach the high-resolution cameras of Mariner would show only a very small area of clouds, much smaller than the scale of the searched-for features, and thus a wide-angle capability was required.

Preparing for Launch

Before launch, during the summer of 1973, an almost true-to-life launch was simulated and carried off at the Mission Control and Computing Center at JPL (Fig. 4-11). Members of the

Fig. 4-11. During the summer of 1973 an almost true-to-life launch was simulated by computers. Personnel to be involved in the mission were trained in this way for the actual mission operations.



mission operations system team spent hours of intense concentration as the various teams went through the exercise of a mock launch and initial collection of data from the simulated flight. This exercise tried out all the ground systems needed to support the spacecraft on its long mission.

Meanwhile, the Mariner Venus/Mercury spacecraft was shipped from the Boeing plant on Friday, June 30, 1973, to JPL, where it went through exhaustive tests in the solar simulator, as discussed above. The spacecraft left the Laboratory in early August in carefully packed sections aboard a convoy of specially equipped vans en route to Florida by road. It arrived at the Air Force Eastern Test Range at Cape Kennedy on August 11, 1973, and was placed in Building AO's spacecraft checkout area for final verification tests. In providing launch operations, the John F. Kennedy Space Center handles scheduling of test milestones and review of data to assure that the launch vehicle has met all of its test requirements and is ready for launch.

Atlas/Centaur 34 was erected on Complex 36's Pad B in July 1973. The flight spacecraft was moved into the Explosive Safe Facility on September 25 for installation of ordnance and loading of its hypergolic propellant. It was encapsulated for mating with its launch vehicle in mid-October.

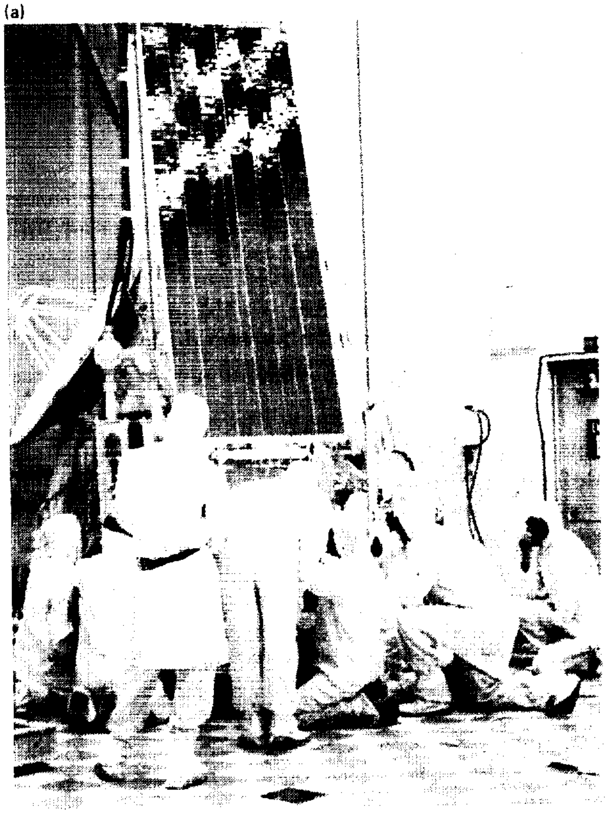
A flight events demonstration test took place successfully during the third week of October to assure that the space vehicle was electrically ready for final launch preparations. The test included running the computer and programmer through post-launch events and monitoring the data to assure correct response to all signals when the umbilical was ejected.

About 10 days before the planned launch, the spacecraft was mated with Atlas/Centaur and further electrical tests were conducted (Fig. 4-12). The Composite Electrical Readiness Test for the overall space vehicle took place a few days prior to launch to verify the ability of the launch vehicle-spacecraft combination to go through post-liftoff events. Range support elements participated along with the spacecraft and launch vehicle just as during a launch.

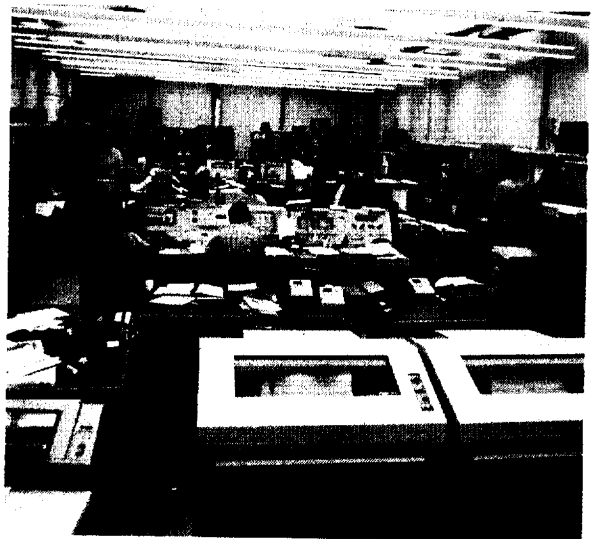
The launch (T)−1 day functional test involved final preparation in getting vehicle and support ready for launch, preparing ground support equipment, completing readiness procedures, and

Fig. 4-12. On arrival at Kennedy Space Center the spacecraft faced another series of prelaunch tests: (a) system test in the AO hanger; (b) a computer operator supports the system testing; and (c) the complex of computers and recording instruments keeps watch over the spacecraft and records the results of all the tests.

(a)



(b)



(c)

installing ordnance on the launch vehicle (Fig. 4-13). The countdown was picked up at T−600 min. All systems were checked against readiness procedures, establishing the integrity of the vehicle and ground support equipment interface prior to removing the tower at T−120 min. Cryogenic propellants of liquid oxygen and liquid hydrogen began to flow into the launch vehicle's tanks at T−100 min, culminating in complete vehicle readiness at T−1 min. The terminal count began with monitoring all systems and topping off the venting propellant and purge systems. At T−10 sec, the automatic release sequence was initiated and the space vehicle was cleared for liftoff.

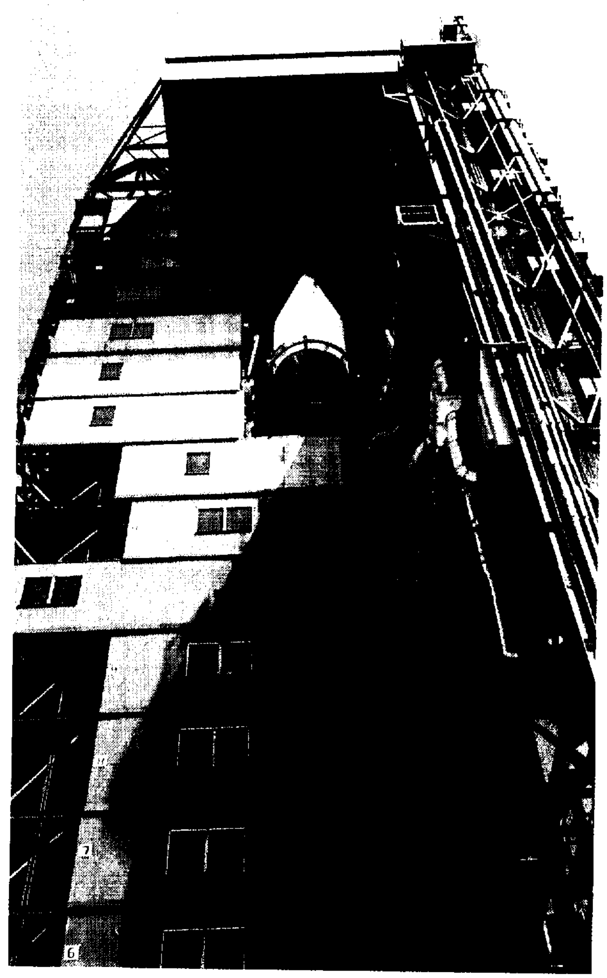


Fig. 4-13. At last Mariner Venus/Mercury, within its protective shroud, is hoisted up the gantry for mating with the Atlas/Centaur launch vehicle.

Chapter 5

Venus Bound - Success and Near Failure

FOR BEST SCIENCE RETURN, the spacecraft had to be launched during a short, 1.5-hour "window" on November 2, 1973. All had to be ready: people, electronics, a worldwide operation—men and women at the Jet Propulsion Laboratory in Pasadena, at tracking stations around the world, at the launch center at Cape Kennedy where the gleaming spacecraft protected by polished thermal blankets rested securely within the shroud atop the Atlas/Centaur on Launch Complex 36B.

All was ready for the epic mission to explore Mercury, closest planet to the Sun, mothlike orbiter in the solar glare; the final countdown had proceeded without a hitch. Then, at 12:45 a.m. Eastern Time, within a few thousandths of a second of the scheduled launch time, Atlas/Centaur No. 34 blossomed into life as its triple engines turned night into day at the launch complex and pounded the eardrums of observers outside the blockhouse. Mankind's first explorer of the planet Mercury was on its way (Fig. 5-1).

For about 15 seconds Atlas/Centaur 34 rose vertically, then began its programmed pitch along its path toward space. Exactly as scheduled, the outer engines of the Atlas lost their fiery exhaust trails at just over two minutes after liftoff and

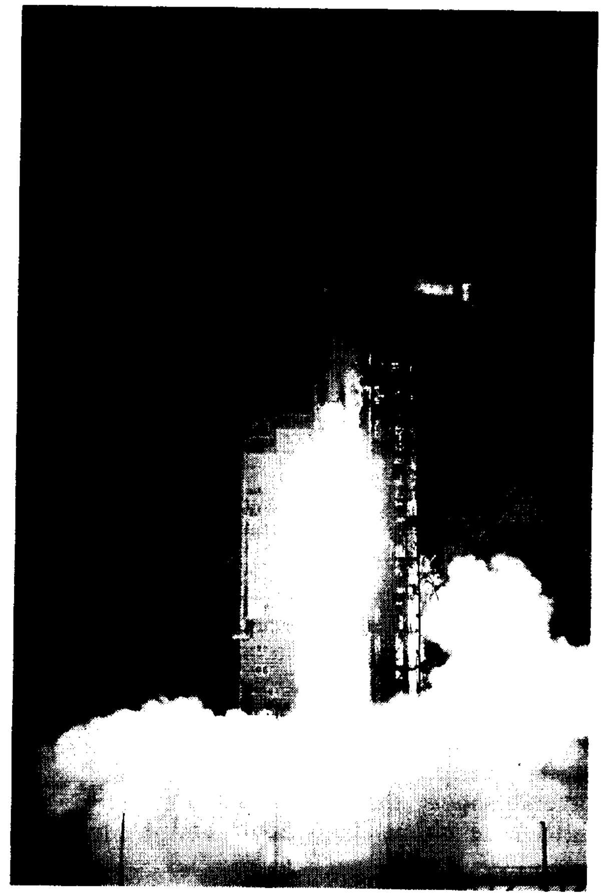


Fig. 5-1. Within a few thousandths of a second of the opening of the launch window, Mariner was sent on its way to Mercury: November 2, 1973, 9:45 p.m. PST.

were jettisoned. Almost two minutes later the fire also died in the main engine. The Centaur upper stage flew free of the Atlas bulk, as an explosive charge sliced through the interstage adapter and retro rockets slowed the spent booster preparatory to its tumbling back into the Atlantic Ocean. Within 12 seconds of Atlas engine cutoff, the bright nucleus of the Centaur's twin engines blossomed in the night sky, to burn fiercely for 5.1 min to push the spacecraft into Earth parking orbit at an altitude of 188 km (117 mi) and a speed of 28,046 km/hr (17,428 mi/hr).

Silently the Centaur and the spacecraft moved weightless nearly a third of the way around the Earth. Again the Centaur's engines erupted into flame, expanding exhaust jets into the vacuum of space. The Centaur and its payload bounded forward in orbit, breaking free of Earth's gravity within 2.25 min at a speed of 40,969 km/hr (25,458 mi/hr) headed backwards along Earth's orbit around the Sun.

Robbed of some of Earth's orbital motion, the spacecraft and the Centaur could no longer balance orbital action against the pull of the Sun's gravity. They began to fall toward the center of the Solar System, following a long orbit around the Sun that would take them ultimately to the orbit of Venus.

About a minute and a half after the Centaur engines shut down, the spacecraft separated from the Centaur. Then, 8 1/2 min later, the spent rocket turned and blew out its remaining propellant through the rocket nozzles to thrust it away from a trajectory that might cause it to tangle later with the spacecraft or crash onto the surface of Venus. Now Mariner Venus/Mercury was on its own: a true spacecraft in its natural environment. Now its name was Mariner 10. Pyrotechnic squibs were fired aboard the spacecraft; its various movable elements unfurled and extended. Mariner 10 had reached maturity as a spacecraft in its cruise configuration.

Very soon after launch, the planet-viewing experiments were turned on, a first time for planetary missions. The aim was to calibrate the instruments in the well-known environment of the Earth-Moon system. The charged particle telescope was turned on within 3 hours of liftoff, the ultraviolet experiment within 7 hours, and the TV cameras shortly thereafter. First TV pictures of Earth were obtained 16 hours and 15 minutes after liftoff.

There were some problems. The two thermal strap-heaters surrounding the aluminum lens barrels of the cameras were designed to hold the camera system at a temperature of 4 to 15°C (40 to 60°F). But they failed to operate as programmed following launch. Mission controllers, watching the engineering data coming back to the Mission Operations Center, saw that the heaters were not activated. Quickly a command was sent to the spacecraft to deactivate the heaters and then to activate them by triggering the relay switch, which seemed to have stuck. Nothing happened. The telescopes continued to cool down.

There was concern that without the heaters operating the television cameras would cool down too much and affect sensitive optics so as to distort pictures of the planets and cause a degradation of camera focus. Part of the problem was caused by the screening of the spacecraft against solar heating. It was so protected by a sunshade and by surface coatings and thermal blankets that when the camera heaters failed to come on, the cameras began to cool. Engineers from JPL and Boeing studied the problem to determine how heat might pass from the rest of the spacecraft in place of that missing from the heaters. They found that the thermal insulation of the spacecraft was so good that there was no way to heat the cameras from the spacecraft itself. The fall in temperature had to be lived with. They also checked the backup spacecraft poised at Cape Kennedy in an attempt to determine what might have caused the relay to stick. Had this problem degraded the spacecraft capability to an unaccepted degree, it would have been necessary to launch the backup.

Fortunately, the cooling stabilized at an acceptable level, and the cameras did maintain their sharp focus. The lens elements and the optical tube elements were self-compensating to changes in temperature. But an ever-present danger was that the Invar rods might contract, fracturing the vidicon potting compound if the temperature fell below −40°C (−40°F). Project scientists halted this temperature drop by keeping the vidicons switched on to maintain some heat within the cameras. Normally the vidicons would have been rested in the cruise between the planets, but it was considered prudent to change this mode of operation and take the chance that the lifetime of the vidicons might be shortened somewhat rather than risk the cameras' becoming too cold. This being done, the temperature of the cameras stabilized, at low but livable values—the vidicons were about −10°C (+14°F), the backs of the optics were −20°C (−4°F), and the telescope fronts were about −30°C (−22°F).

Mariner's cameras transmitted good pictures of the Earth and the Moon despite the temperature problem. The pictures of Earth (Fig. 5-2) provided stereo photographs of clouds with revealing depth and structure. They appeared to be the clearest pictures yet received from a television camera in space. If the spacecraft returned similar-quality pictures from Venus, the project could obtain a completely unprecedented look at the brilliant clouds of that mysterious planet.

In all, Mariner 10's cameras provided a series of five Earth mosaics (Fig. 5-3) within the first few days of flight. These mosaics revealed intricate cloud patterns at about the same resolution expected during the Venus flyby. The Earth pictures could provide valuable comparisons with the Venus clouds. Earth observations also provided in-flight verification of the cameras' "veiling glare" performance, thus confirming that the preflight calculations of settings of camera exposures for Venus were correct. This was important, since Venus encounter geometry did not allow an incoming far-encounter sequence to check the exposures.

Fig. 5-2. A few hours later it was testing its cameras and sending photographs back of its home planet.

Another problem arose almost at the beginning of the flight when, on November 5, the plasma science experiment was turned on. Scientists were surprised to find that no solar wind particles were being observed. There appeared to be a good vacuum in the detectors, and the device was scanning back and forth as it should. Engineers performed a series of tests and sequences of switching commands without positive results. One possibility was that the instrument door had failed to open so that plasma could not enter the detector. Another was that the high-voltage sweep was stuck at the high end, thus permitting only a few high-energy particles to register. The operation of this experiment was, unfortunately, restricted throughout the mission, and it was concluded that the protective door had failed to open fully. However, plasma data were obtained by the scanning electron spectrometer part of the instrument, which was unaffected by the failure of the door.

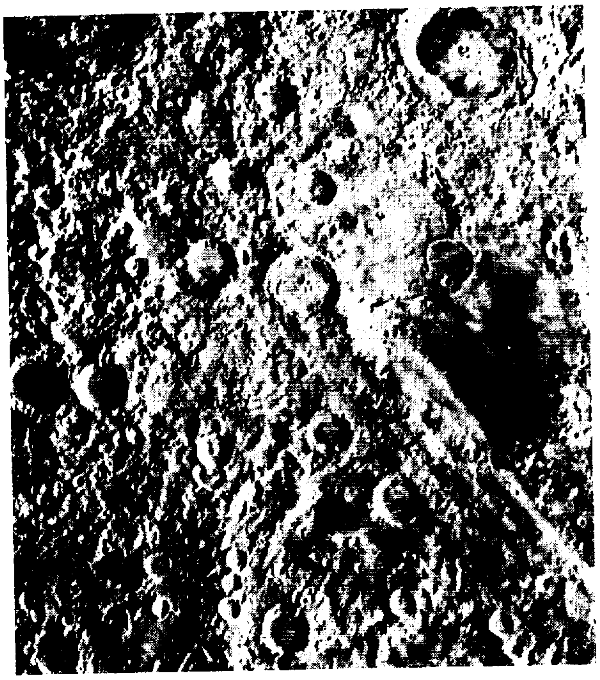
As the spacecraft left Earth, the ultraviolet air glow instrument looked back at the home planet, observing the same emission regions that it expected to check later at Venus and Mercury. Lyman-alpha hydrogen emission was recorded, together with helium emission at 584 angstroms.

All subsystems of the spacecraft were performing exactly as expected. The trajectory was also very good; less than 8 m/sec (27 ft/sec) of the spacecraft's total maneuvering capacity of 120 m/sec (396 ft/sec) was expected to be needed to move the Venus aiming point of the spacecraft and change the arrival time about 3 hours to bring Mariner 10 to its later pass within 1000 km (600 mi) of Mercury's surface.

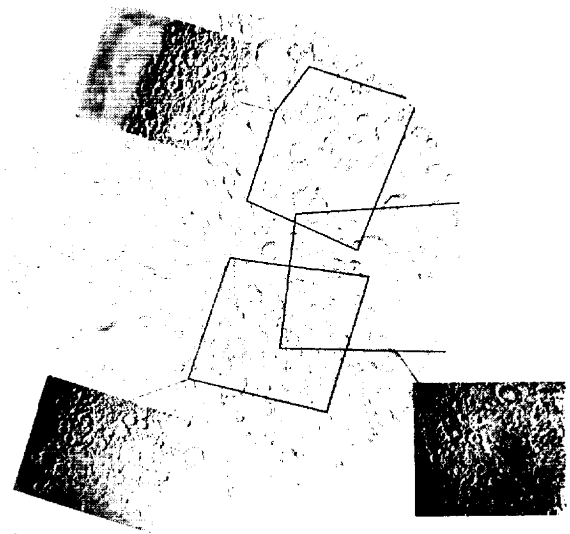
Mariner 10's series of five Earth mosaics was intermixed with six mosaics of the Moon (Fig. 5-4) within the first week of flight as calibration tests for the Mercury encounter. The path of

Fig. 5-3. In the next few days mosaics of Earth and Moon were built up as imaging team members tried out the cameras to see if the failing heaters had degraded the optical system. The Earth is revealed here in great detail, auguring well for the capability of Mariner to produce pictures of details in the clouds of Venus.

Fig. 5-4. The good quality of the Moon mosaics made promising the prospect of later photographing the surface of Mercury, which was believed to be a Moonlike body.

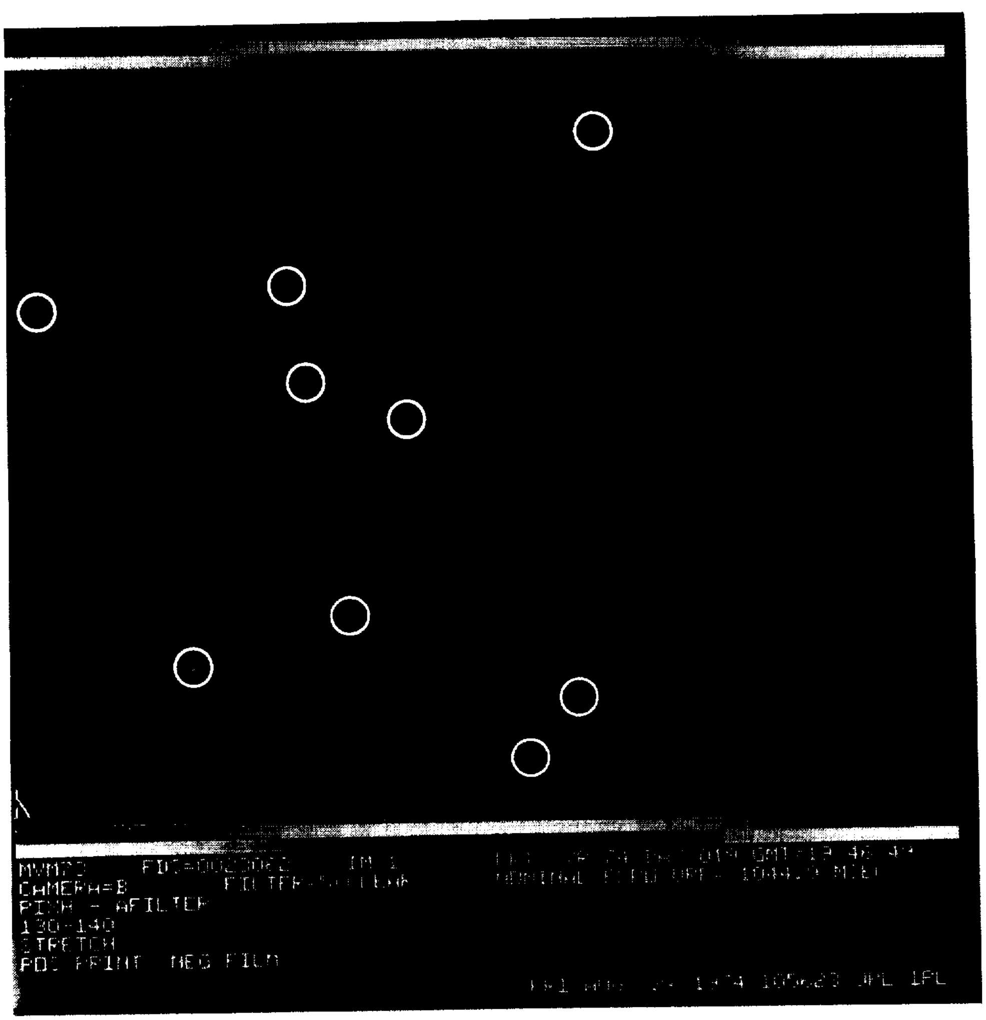


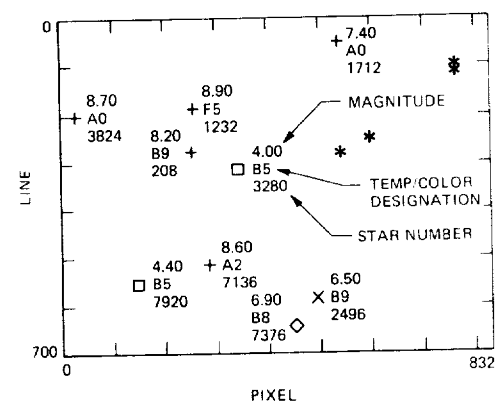
(a)



(b)

Fig. 5-5. As it passed the Moon, Mariner provided views of the north polar regions needed to update lunar maps. One of these pictures is shown in (a); (b) shows how the new photographs can be applied to fill in the poor details so far obtained of the lunar north pole.



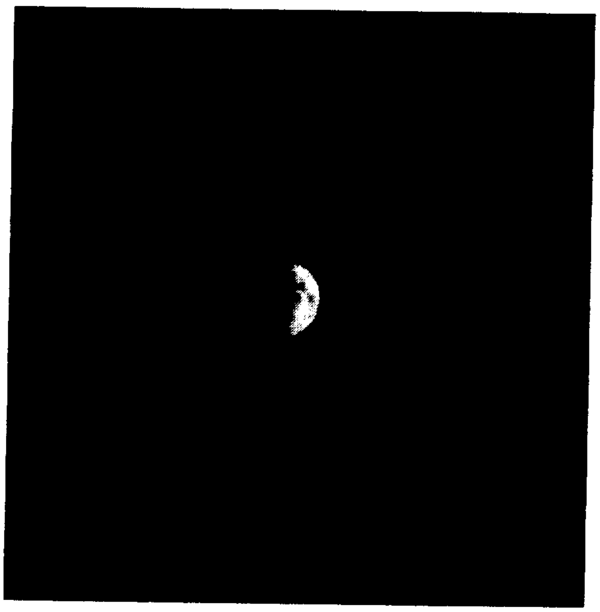


(b)

Fig. 5-6. Mariner's cameras also checked their sharp focus on stars to show that they had not degraded from the heater failure. A stellar field is reproduced in (a); (b) identifies the stars photographed.

Mariner allowed images to be obtained of the north polar region of the Moon (Fig. 5-5), which, because of constraints on paths of other space vehicles, had previously been covered only obliquely. The Mariner 10 photographs provided a basis for cartographers to improve the lunar control net, the relationship of points on the lunar surface one to another in precise definitions of lunar latitude and longitude of craters and other features. The exercise in lunar cartography provided a useful prelude to applying the same techniques to map Mercury using the images to be obtained during the flyby.

Diagnostic tests were conducted on November 6, including photography of stars (Fig. 5-6) and additional tests on the Moon (Fig. 5-7). The Moon tests, as well as providing better information about how the TV system was performing,



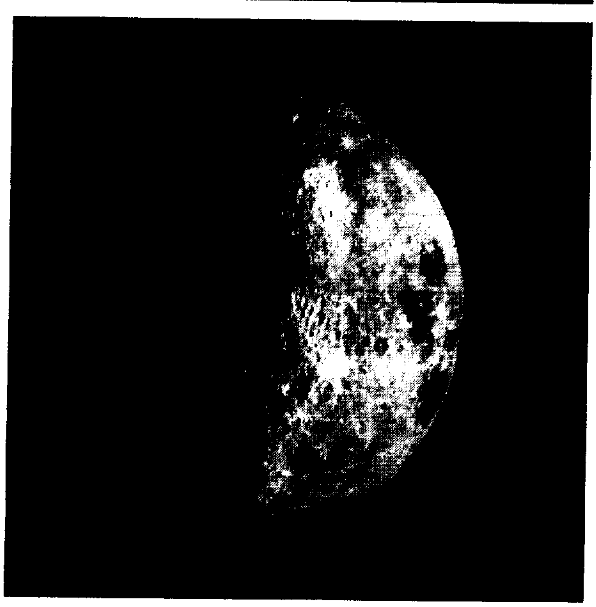


Fig. 5-7. Gradually the Moon was left behind and Mariner 10 was heading for Venus.

allowed scientists to evaluate the practicality of proposed measurements of the diameter of Mercury. At this stage of the mission, optical performance of the television system continued to be good even though the TV optics had not yet stabilized in temperature. As of November 7, Mariner 10 had returned almost 900 pictures to Earth. Experimenters were enthusiastic about the excellent quality. The Moon pictures recorded objects a mere 3 km (2 mi) across (Figs 5-8 and 5-9). Since the pictures to be returned from Mercury were expected to be of three times higher resolution than those of the Moon, there was good reason for excitement. At last, it seemed, mankind would have a chance to resolve those dusky markings on the innermost planet, those indistinct features that earlier astronomers had interpreted as Marslike, even erroneously with linear "canal" type features. Another test conducted was photographing the Pleiades cluster in the constellation of Taurus: a galactic cluster in the Milky Way which is visible to the unaided human eye as seven faint stars and is often called the "Seven Sisters". These stars are about 20,000 light years from the Sun and are immersed in nebulosity. A total of 84 pictures were taken, verifying the focus of the television system.

On November 8, commands were executed in the spacecraft to calibrate the charged particle telescope. Scientists were pleased to see good data. Also, the scanning electron spectrometer of the plasma science experiment produced excellent data. These data were routed, as they arrived, to the NASA-Goddard Space Flight Center in Maryland so that members of the science team at Massachusetts Institute of Technology and at Los Alamos Scientific Laboratory were able to follow the test in real-time by telephone links with

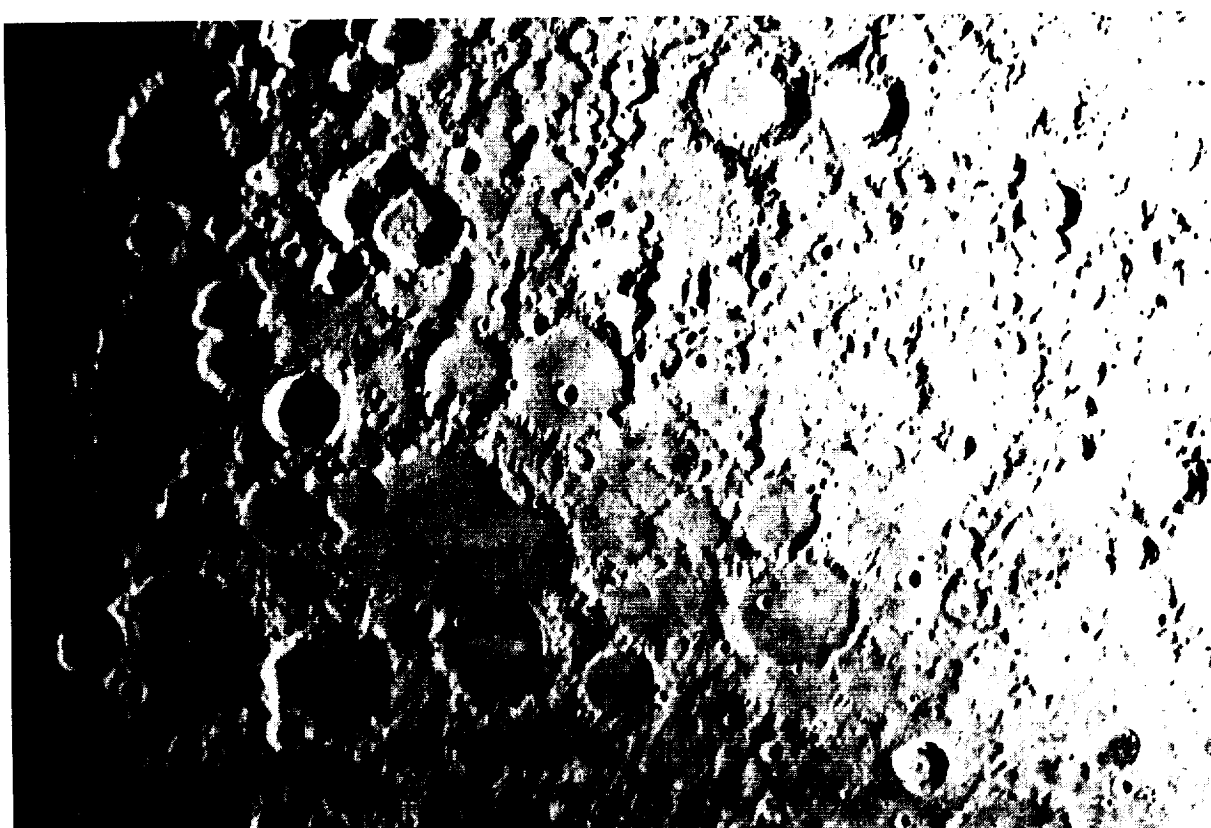


Fig. 5-8. The imaging team was enthusiastic about the quality of the lunar images. The close-ups obtained were excellent.

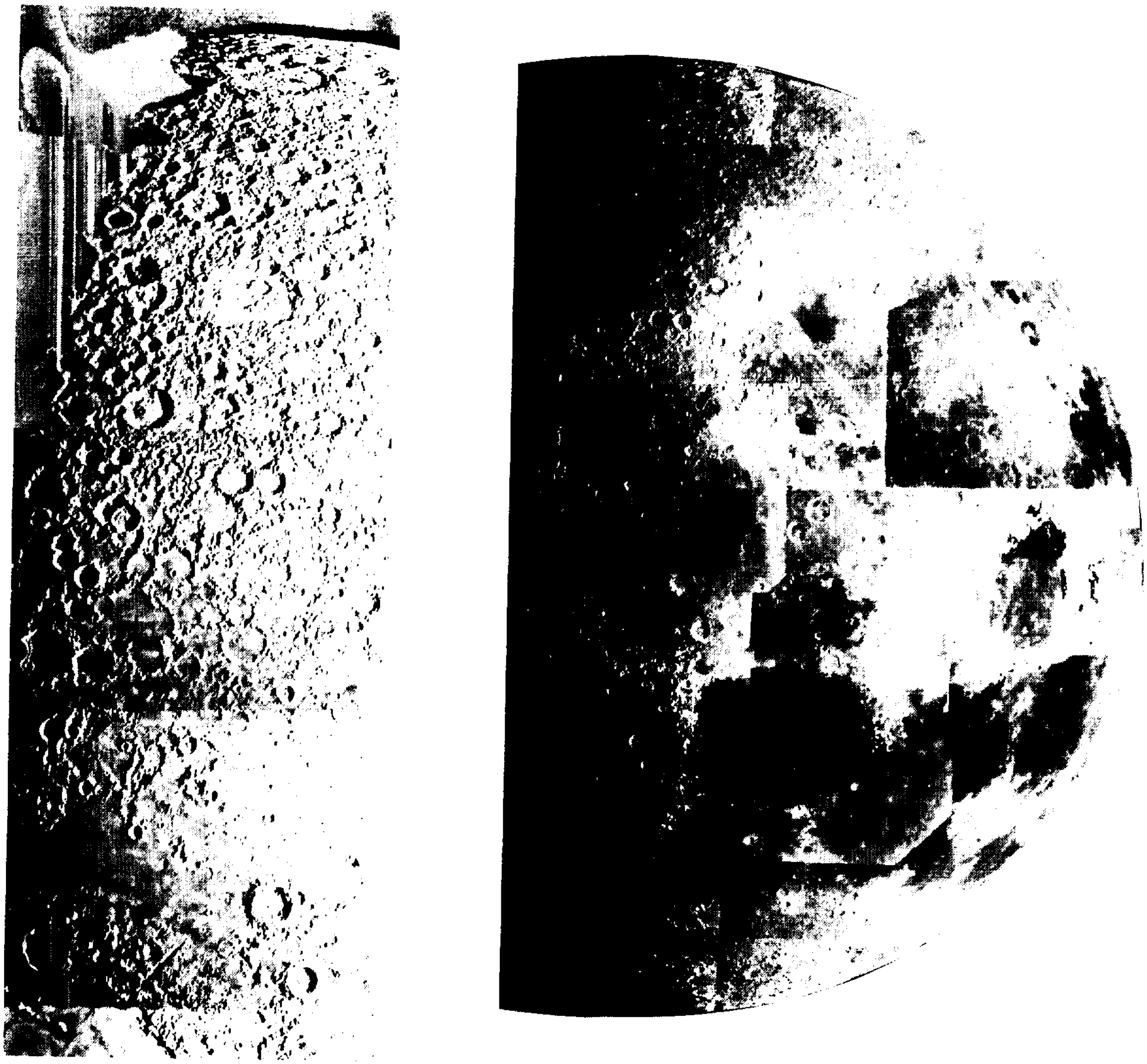


Fig. 5-9. The details revealed on the Moon's surface showed the capabilities of this new television system for planetary photography. The computer-enhanced terminator regions showed that the system would also provide great detail in the terminator regions of Mercury. The small picture is a mosaic; the computer-enhanced terminator regions are shown alongside.

NASA-Goddard. The team was able to compute approximate plasma density, electron temperatures, and the flux of charged particles by using this real-time data. The Principal Investigator, Herbert S. Bridge, stated that although the experiment was "painfully" degraded with apparent loss of the data from the scanning electrostatic analyzer, valuable information concerning the solar wind was being obtained, and this experiment was still expected to produce new information about the interaction of the solar wind with Venus and Mercury later in the mission.

By November 11, over 2000 commands had been successfully sent from the Mission Operations Center to the spacecraft. Of these, 1019 were to update the central computer and sequencer preparatory to making the first trajectory correction maneuver for the spacecraft. By this time the navigation teams had determined the trajectory of the spacecraft and knew that, if uncorrected, Mariner 10 would fly by Venus on the wrong side of the planet, some 55,000 km (34,000 mi) off the aiming point and 3 hours later than desired, and would miss Mercury. The spacecraft had now to be turned and reoriented in space so that its rocket engine could be fired for a short period and apply a change in velocity to the spacecraft in the right direction to ensure that it would arrive at Venus at the right time and place to permit the later encounter with Mercury.

The velocity change required was some 7.8 m/sec (about 25.5 ft/sec or just less than 18 mph), which required the rocket engine to burn for about 20 sec and consume 1.8 kg (about 4 lb) of propellant. On Sunday November 11, project personnel gathered at the Mission Operations Center for a maneuver conference at which the maneuver scheduled for November 13 was given the go-ahead. At 1:45 p.m. PST on that date the maneuvering sequence started aboard Mariner 10 with the command that maneuver events would start clocking at the next hour pulse within the spacecraft. This pulse occurred at 2:38 p.m., and at three sec after 3:00 p.m. the gyros began to whirl within Mariner. Just over an hour later the cold jets at the tips of the spacecraft solar panels spurted nitrogen gas into space and the spacecraft began its roll turn, taking about 4.5 min to roll through 49 deg. Then, equally as abruptly, opposing nitrogen jets stopped the roll. A few minutes later jets of nitrogen spurted from other thrusters mounted on the outriggers that support the high-gain antenna and the magnetometer. The spacecraft started to slowly pitch over, taking another 12 min to pitch through 127 deg before opposing jets stopped the pitch. Now it was ready for the hydrazine rocket engine burn. A valve in the propellant system opened. Nitrogen gas pressing against a rubber diaphragm in the propellant tank forced hydrazine into the rocket thrust chamber, where it was decomposed by a catalyst to produce a hot jet. The thrust lasted for the required 19.9 sec; then the valves closed and the engine shut off.

Four minutes later the central computer and sequencer started the pitch jets operating, followed by the roll jets, to return the spacecraft to its correct orientation with respect to the Sun and the stars. Then the gyros were switched off. At 5:08 p. m. the first trajectory correction maneuver had been completed.

Meanwhile the tracking data were being examined by the navigation staff at JPL to check the effects of the maneuver. There was momentary anxiety at the Operations Center when telemetry signals from the spacecraft indicated that the Canopus tracker had lost the star. It seemed that a bright particle had moved past the spacecraft—perhaps a meteor or a particle from the spacecraft itself—and attracted the star sensor. But soon Canopus was reacquired and the spacecraft returned to normal by 6:40 p.m. PST.

As doppler data were analyzed, the performance of the maneuver looked good. The navigation team had been able to monitor both the roll and the pitch turns and to ascertain that the velocity change of the main engine thrust caused a doppler shift of 71 Hz, while 72 Hz was required. This corresponded to an error of 1.5%. However, analysis of tracking data for 15 days after the trajectory correction maneuver was needed before the exact trajectory could be determined.

By November 28, it was known that the spacecraft was headed much closer to its required rendezvous with Venus, but there was still a relatively small error of 1380 km (860 mi) too far from the planet and an arrival time 2 min early over that required (see Fig. 5-10). A scheduled

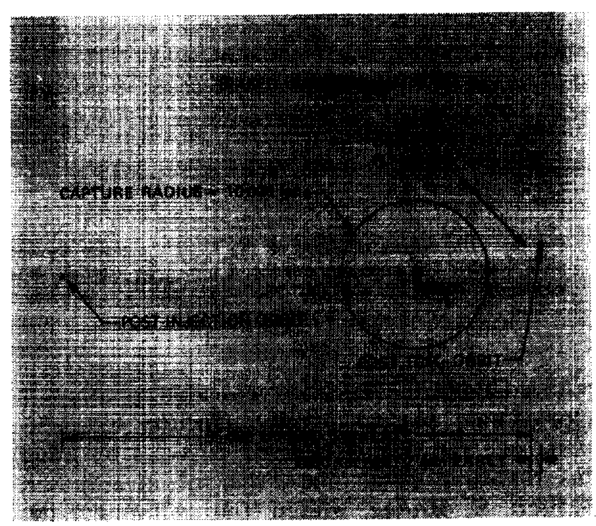


Fig. 5-10. By this time navigators had checked the aiming point at Venus and could prepare for a first trajectory correction maneuver to change the post-injection orbit to the desired flyby point. This was done by TCM-1 a few days after the Earth-Moon system had been left.

further trajectory correction maneuver would have to be made later in the mission to refine the position and time of encounter. Two maneuvers before reaching Venus had always been a part of the mission plan.

However, other troubles had shocked operations personnel. On November 21, the gyros were commanded on to put the spacecraft through a roll calibration maneuver. Immediately, the flight data system reset itself automatically to zero, but it was not known if this uncommanded reset was a problem in the spacecraft power or in the grounding system or was a sensing error of the flight data system itself. The roll calibration maneuver was postponed.

It was not until two weeks later, on Friday, December 7, 1973, that Mariner 10 performed a successful roll calibration maneuver and a calibration of the high-gain antenna. Again during the turn-on of the gyros for this maneuver, the flight data system automatically reset itself to zero as it had done previously. But the most significant and ominous power-related problem did not occur until nearly a month later, January 8, 1974, when the spacecraft automatically switched from its main to its standby power chain. This automatic switchover was irreversible: it was of concern primarily because of the possibility of a fault common to both power circuits causing the backup power circuit to fail also and thus raising the possibility of the mission's being ended right there. So, following this power problem, extreme caution was exercised for some time in changing the power status of the spacecraft and in maneuvering relative to the Sun, the latter to avoid an automatic switchover from solar panel to battery power.

There was another problem connected with the high-gain antenna which seemed to stem from its low temperature. On Christmas Day 1973, shortly before 1:00 p.m. PST, a part of the feed system of the high-gain antenna failed and caused a drop in signal power emitted by the antenna. Mission controllers tested the system, issuing diagnostic commands to the spacecraft. They deduced that a joint in one of the feed system's two probes may have cracked or fractured due to temperature changes during the flight. The problem was regarded as severe because it would prevent real-time TV sequences from being transmitted to Earth at Mercury encounter so that less area of the planet's surface could be covered by the photomosaics.

On December 29, the feed system healed itself. The high-gain antenna performed normally again. But the joy of the engineers was short-lived. Within four hours the fault developed again. Analysis indicated that the problem might have been caused by the low temperature of the feed system, and it was hoped that by the time the spacecraft reached Mercury the antenna temperature would be high enough to clear the fault and permit full operation of this antenna so that the full complement of mosaics would be obtained.

However, the antenna problem caused cancellation of some planned ultraviolet spectrometer airglow experiments, together with a roll calibration maneuver and other tests of the spacecraft. Engineers devised tests using duplicate hardware on Earth to simulate possible causes of the high-gain antenna problem. But as the orientation relative to the Sun changed and there was some heating of the antenna feed, the problem cleared up again by itself on January 3. A predetermined contingency plan was immediately put into effect by Mission Operations to position the high-gain antenna so that the Sun would continue to warm the feed. By positioning the antenna to gather some solar heat, the temperature was maintained well above the temperature at which the high-gain antenna problem had originally developed. In addition to thermal considerations, the new position of the high-gain antenna was selected to direct a side lobe of the antenna pattern toward Earth, since the side lobes carried more radiated power than the low-gain antenna.

After recovery on January 3, the high-gain antenna again failed on January 6, and the antenna was pointed back to Earth and use of the side lobe discontinued. Meanwhile, other events had occurred. On December 14, 1973, the solar panels were tilted 25 deg off the Sun to reduce the surface temperature of the panels by approximately 10°C (18°F). On December 18, the scan platform was also tilted to its maximum so that the ultraviolet airglow spectrometer could make new measurements of emissions from interstellar helium gas in a direction opposite from the Sun.

On December 19, the gyros were turned on and another roll calibration maneuver made. This time there was no power-on reset in the flight data system as had occurred during the previous maneuvers. The spacecraft seemed to be behaving

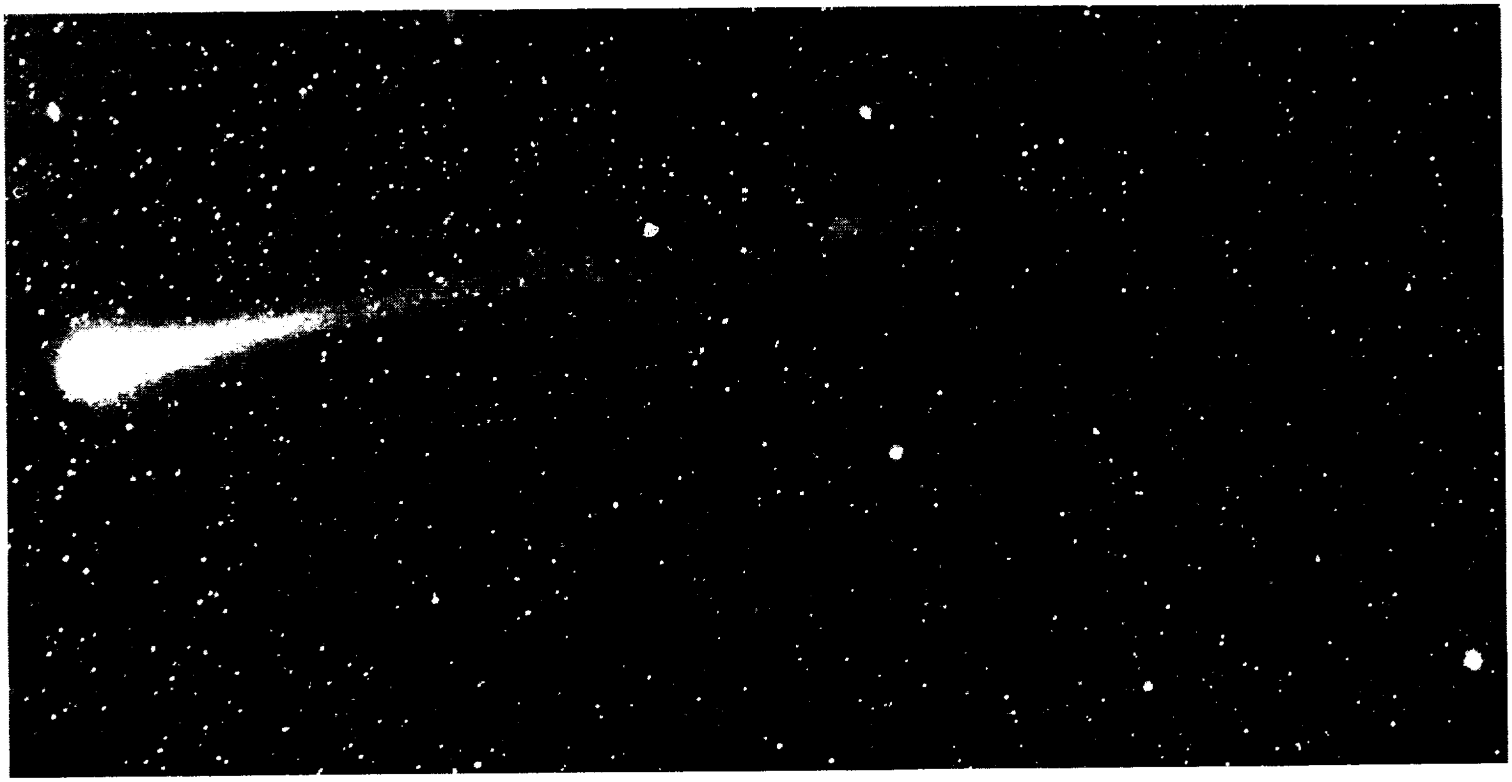


Fig. 5-11. On the way to Venus an opportunity arose to observe the Comet Kohoutek from Mariner 10. Although images were not obtained because the comet was much fainter than originally expected, ultraviolet scans provided new information on the comet that could not be obtained from Earth. (Photo: Table Mountain Observatory)

quite neurotically and confounding its designers and controllers.

Early in January the scan platform aboard the spacecraft was slewed so that the ultraviolet airglow spectrometer could be ready for observations of the Comet Kohoutek (Fig. 5-11). The prime objective was to obtain unique observations of Kohoutek in the ultraviolet region of the spectrum which could not be obtained from Earth or from orbiting vehicles due to the Earth's hydrogen corona. Mariner 10 was well outside the hydrogen corona, thus being in a superior position to Skylab, which was also being used to observe the comet. Observations began with passive ultraviolet measurements of the tail of Kohoutek starting January 9 and concluded with the passage of the comet's nucleus through the field of view by January 17. Active ultraviolet scanning and TV imaging of the comet took place toward the end of the month. Neutral hydrogen emission intensities were measured by Mariner as far as 17 deg from the comet's nucleus compared with only 2 deg for the Skylab-based observations from within the Earth's hydrogen corona.

The attempt to photograph comet Kohoutek was not, however, successful, mainly because the comet disappointed everyone by being such a faint object—nearly 50 times less bright than anticipated. The comet was too faint to reveal any useful information in the TV pictures from Mariner. But Mariner's ultraviolet spectrometer did obtain some very good Lyman alpha (neutral hydrogen) radiation measurements through the comet's tail and into the nucleus. Preliminary results of this ultraviolet scanning showed a very large hydrogen corona to the comet, having a diameter of about 20 million km (12.5 million mi).

The next major event in the Mariner 10 mission was the second trajectory correction maneuver required to refine the flyby of Venus to a greater precision, making it possible to reach Mercury after the Venus encounter. On January 16, some of the preliminary commands for the maneuver were sent to the spacecraft and stored in its memory within the central computer and sequencer. The objective was to make sure that Mariner 10 would fly through a 400-km (248-mi) diameter "hole in the sky" which lay about 16,000 km (10,000 mi) to the right and in front of Venus as seen from the approaching spacecraft. The gravity of Venus would bend Mariner's path from that aiming point to pass within 5784 km

(3594 mi) of Venus's surface about 10:00 a.m. PDT on February 5.

The navigation team redetermined the orbit of the spacecraft following the trajectory correction maneuver performed shortly after launch by processing over 60 days of tracking data consisting of 2600 measurements of the distance of the spacecraft from Earth. If the error at Venus were left uncorrected, the spacecraft would miss Mercury by 1.5 million km (nearly 1 million mi).

On January 21, at 11:50 a.m. PDT in response to stored commands, Mariner rolled itself about 46 deg, pitched over nearly 35 deg, and then, 24 min later, fired its rocket engine for 3.8 sec to change the spacecraft velocity by about 1.3 m/sec (4 ft/sec). At Mission Operations, project personnel were jubilant when the doppler frequency was measured as having shifted 17.41 Hz, which was within 0.04 Hz of the required amount. Following another 10 days of tracking, the navigation team confirmed that the flyby point was within 27 km (17 mi) of the aim point. All science equipment was working well, ready for Venus encounter; the cameras were stabilized in temperature; the only science problem was the still-closed door of the plasma experiment. But other troubles beset the spacecraft.

On January 28, Mariner started a series of eight calibration rolls that were to be completed in 79 min. At the end of each roll the scan platform was moved to obtain records of the diffuse ultraviolet emissions observed over wide regions of the sky. Suddenly, an oscillation occurred in the roll channel of the attitude control system, causing expulsion of attitude control nitrogen gas at a disastrous rate. As the gas pressure telemetry data dropped inexorably, mission controllers knew they were watching a spacecraft die. In the hour that it took to recognize, analyze, and respond to the problem, some 16% of the spacecraft's attitude control gas had been ejected into space. W. I. Purdy, the Guidance and Control Analyst, hastily called from a meeting, quickly determined that the gas loss was a result of a gyro-induced instability. He commanded gyros off, and the gas loss stopped. The nitrogen gas supply had dropped from 2.7 to 2.1 kg (6.0 to 4.7 lb).

Later analysis showed that the gas loss resulted from a mechanical oscillation of the spacecraft induced by impulses from the jets mounted on the extreme ends of the solar panels. Following extensive analysis, mission controllers issued commands for the movable solar panels and scan platform to be positioned in such a way as to prevent the oscillation and thus avoid further loss of gas in the future. It was hoped that spacecraft attitude maneuvers and trajectory corrections might be conducted under certain conditions without inducing further gas-consuming oscillations.

But the cause of the problem was not known during the final preparations for the Venus encounter. A gyro malfunction was at that time a viable explanation, and a disastrous, uncontrollable spacecraft spinup was thought to be a possible result if the gyros were turned on again, Thus, the flyby of Venus was now planned to take place under Sun and star reference instead of inertially by gyro control. This presented a hazard to the spacecraft in that Mariner 10 might suddenly swing around to lock onto the bright planet instead of the star Canopus. Project engineers analyzed the characteristics of the Canopus tracker and decided that the design of the baffles to protect the sensor from stray light made the probability of losing lock on Canopus acceptably low. The risk was therefore taken, and Mariner 10 bore down on Venus oriented to the celestial references of the Sun and Canopus. The three-axis gyro system remained idle.

On January 17, during the time that heaters for other Mariner 10 instruments were being turned off in preparation for the second trajectory correction maneuver, the heaters for the TV cameras, which had mysteriously been off since launch, equally as mysteriously came back on by themselves. Actually, the explanation for the failure was that there had been a short in another heater which resulted in biasing the TV heater to its switched-off mode. The "healing" of the camera system was most welcome, since the science investigators had been concerned that the cameras might not operate properly during Venus encounter because their temperature had dropped below freezing. After the trajectory correction maneuver had been completed, the original plan was to turn the heaters on again. But to avoid any risk of affecting the camera heaters, heaters in the same circuit as those for the cameras were left turned off. Mariner had by now warmed up sufficiently in its approach to the Sun so that some of the heaters were no longer needed. On January 23, the movable scan platform on which the TV cameras were mounted was given its final pointing calibration by taking three sequences of test pictures of star clusters. Then the cameras were idled for a week.

By February 4, Mariner 10 was 640,000 km (about 400,000 mi) from Venus and approaching the planet at a speed of over 29,600 km/hr (18,400 mi/hr). On this day, as the high-gain antenna was being moved during a calibration sequence, the feed system problem suddenly righted itself; then a little later it returned, but not as badly as before. Despite all of the spacecraft problems, it appeared that Mariner 10 was capable of conducting the Venus encounter as conceived long before launch. Much credit was due the project personnel who had nursed the neurotic spacecraft through its troubles and had devised ways to continue the mission by operating around the various problems. Everything was now ready for the encounter (Fig. 5-12).

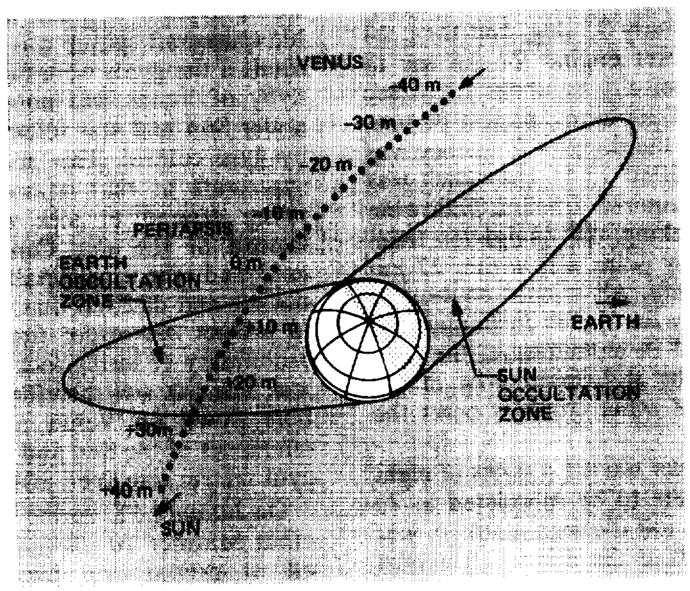
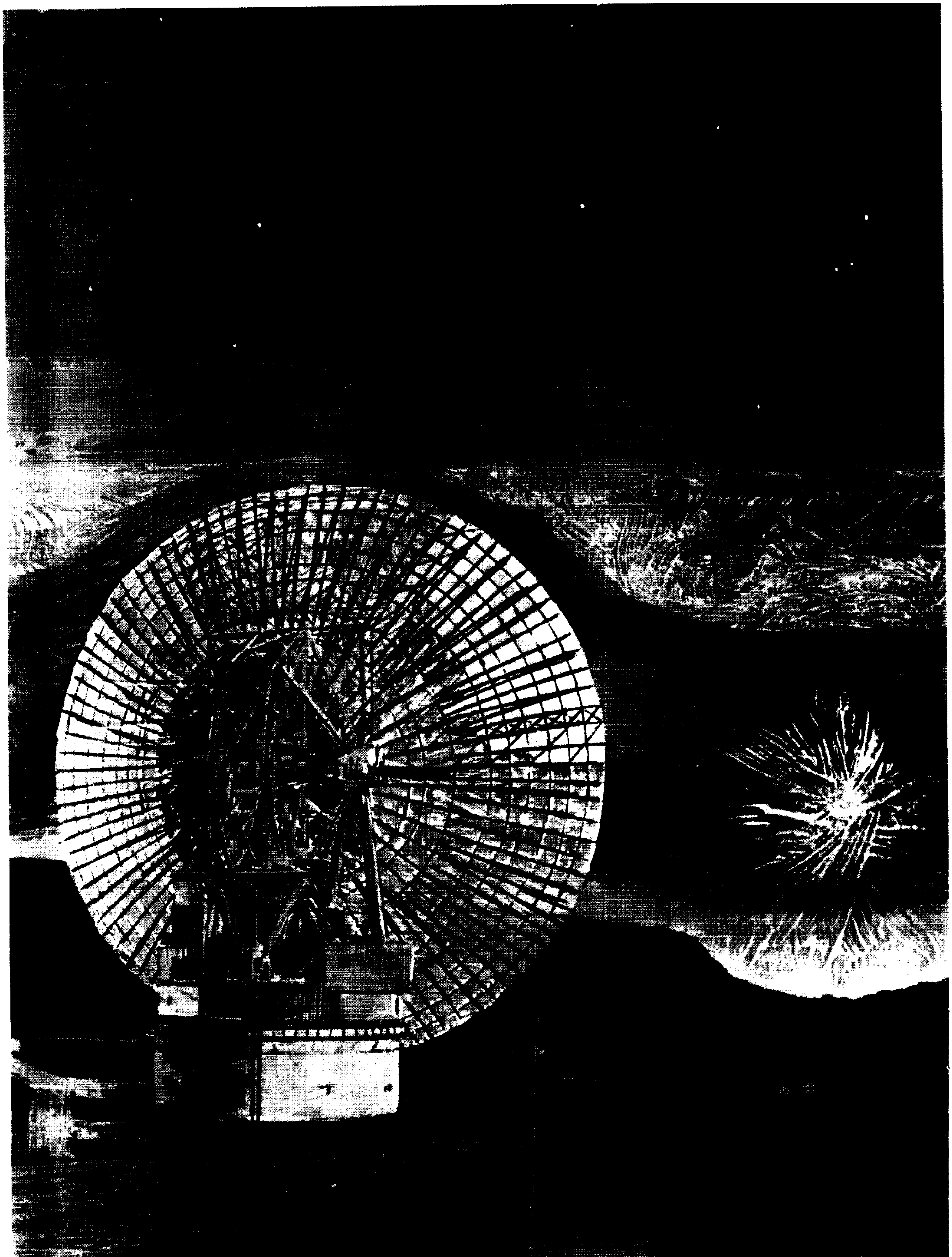


Fig. 5-12. A further trajectory correction maneuver and Mariner 10 was all set for its encounter with Venus.



Chapter 6
Best Seen in Black Light

As MARINER 10 BORE DOWN on the planet Venus, the brilliant jewel scintillated in the clear sky of the Mojave desert, where the Goldstone antenna pointed eastward to pick up signals from the spacecraft. When Mariner 10 was acquired by the 64-m (210-ft) radio antenna, it was about 45 million km (28 million mi) from Earth, approaching Venus from the dark side, its cameras unable yet to photograph the cloud-shrouded planet. At 9:21 a.m. PDT on February 5, 1974, Mariner started to take photographs, but its cameras were still pointed toward space; the first pictures displayed on the screen at JPL were blank.

About 8000 km (5000 mi) from Venus, Mariner 10's television cameras took the first picture of the planet, and shortly after 9:50 a.m. PDT this picture was displayed on the monitor screens. The photo showed the lighted cusp of Venus at the north pole (Fig. 6-1) just 12 min before Mariner 10 made its closest approach of about 5790 km (3600 mi) above the surface of the planet. The scanning sequence of the cameras sent more and more high-resolution pictures of Venus back to Earth, pictures that straddled the terminator boundary between night and day and would have shown detail there if it were present, pictures that curled across the limb of the planet like caterpillars side by side. All showed equally featureless clouds. However, the pictures obtained as Mariner laid tracks across the limb of Venus showed definite haze structure above the limb (Fig. 6-2). Two distinct layers were apparent with definite structure above the limb. This was the type of information that Mariner scientists had hoped for.

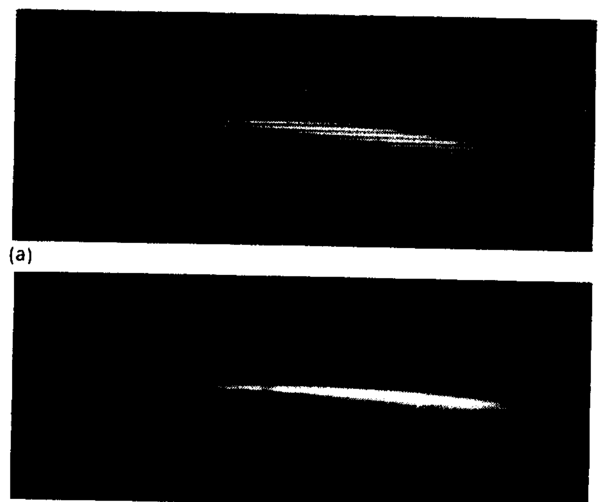

(a)
(b)

Fig. 6-1. The first view of Venus was a fine cusp seen (a) on the television screens at JPL, and (b) processed later to show a clearer image. But there were no protruberances or markings that would indicate cloud tops or structure at the top of the atmosphere.

Michael J. Belton of Kitt Peak National Observatory, a member of the TV science team,

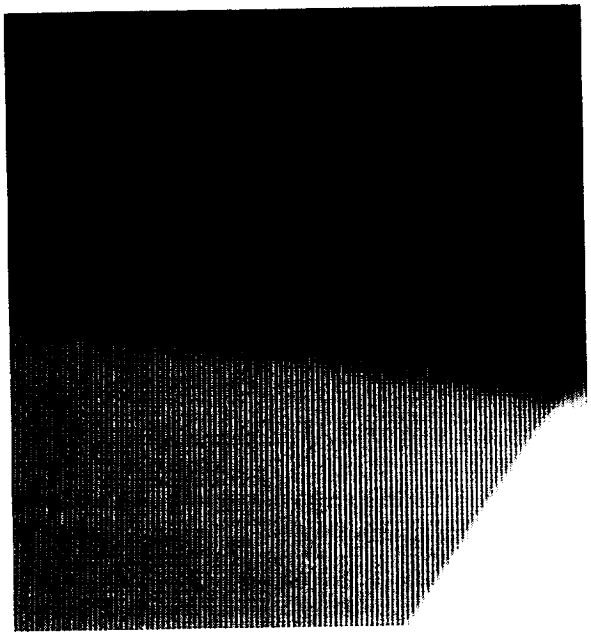


Fig. 6-2. A short while later those same screens at JPL were showing haze layers on the limb—the only details visible on the many images returned from Venus during the close encounter; all the rest of the images showed blank clouds like the top of a bank of fog.

took time off from inspecting the new pictures of Venus to discuss them with science reporters from the national press and overseas. He said the pictures seemed to be getting better as the spacecraft moved away from the planet.

Mariner 10 made its closest approach of 5794 km (3600 mi) at 10:01 a.m. PDT, within one minute of the time scheduled before launch. Then, six minutes later, the spacecraft went behind the planet, and radio signals began to fade as they passed deeper and deeper into the atmosphere. To keep the signals coming back to Earth as long as possible and thus dip as deeply as possible through the atmosphere of Venus, the high-gain antenna on the spacecraft was programmed to turn slightly and direct the signals so that when bent by the planet's atmosphere they would still be received at Earth (Fig. 6-3).

This program was most successful. If Venus had been airless like the Moon, the signals from the spacecraft would have been cut off abruptly at 10:07 a.m. PDT. As it was, the signals continued for several minutes, and scientists were satisfied that they had obtained a completely new probe to great depths of the Venus atmosphere. Since these data were collected simultaneously at two radio frequencies, they were expected to be much better than any earlier radio penetration of the Venus atmosphere.

Four minutes after the tracking station lost lock on the spacecraft signal, the antenna started to search for the signal again as it came around the other side of the planet. Again the signal was picked up and Mariner was tracked to its full emergence from behind the planet. While behind Venus, Mariner had continued taking pictures, which it stored on tape together with infrared data on the temperatures across the night and day hemisphere, fields and particles observations, and scans across the limb in ultraviolet.

Prior to the encounter, the main action was concerned with preparing all the instruments and making sure that the spacecraft followed a precise

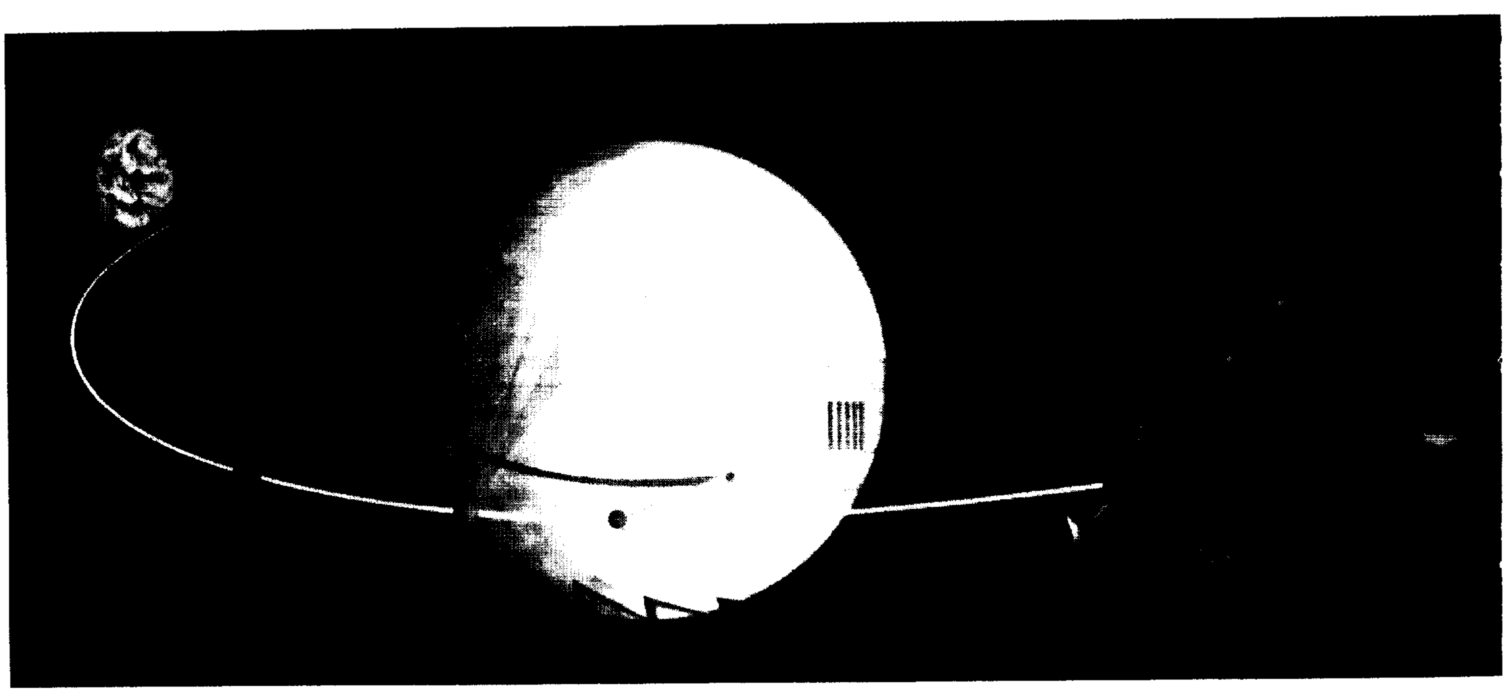


Fig. 6-3. The occultation experiment allowed Mariner's radio signals to penetrate the atmosphere of Venus. Changes to the signals allowed scientists to measure temperatures in the atmosphere and identify layers of clouds at different levels above the surface of the planet.

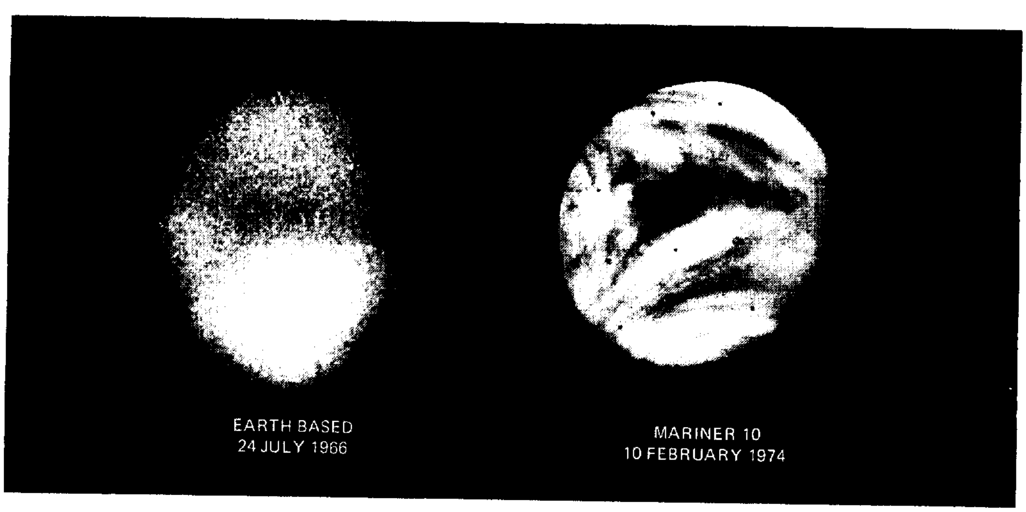
Fig. 6-4. When ultraviolet photographs of Venus came back to Earth as Mariner sped away from Venus, they showed surprising details of atmospheric patterns. This view of the southern hemisphere taken one day after closest approach reveals spiral-like markings and streamline flows. The picture, part of a 36-frame full-planet mosaic, was taken at 10:15 a.m. PDT, February 6, from a range of about 725,000 km (450,000 mi). The pattern of dots is on the face of the vidicon tube and is used to calibrate the image.

path to and beyond the target planet. But when the encounter was successful, the accent changed. With data deluging back to Earth about Venus and its environs, action transferred to the teams of scientists who were literally snatching hold of the output from the computers to interpret this wealth of new information from another world. Did it fit the earlier theories? Did it show anything unexpected? Excitement mounted rapidly as team members struggled with the data records to find answers to these and other questions. Teams assembled from scientists of many different disciplines worked toward common goals, rushing to each other with new items of information to fill gaps in the puzzle.

Meanwhile, the spacecraft emerged from occultation, heading out from Venus toward Mercury. The TV pictures had changed from blue- and yellow-filtered to ultraviolet. In late afternoon, the few members of the press remaining in the von Karman auditorium at JPL, where pictures of Venus were being relayed in real-time for the news media—most of the journalists had left, disappointed at the lack of detail in the first images—were treated to a completely new view of the cloud-shrouded planet. The first ultraviolet pictures displayed on the screens showed intricate cloud patterns (Fig. 6-4). Excitement mounted as scientists identified these markings as close-ups of the indistinct ultraviolet markings recorded on Earth-based photographs (Fig. 6-5).

The best telescopic photographs of Venus from Earth only hint at the cloud patterns revealed in

Fig. 6-5. The ultraviolet markings now photographed in great detail on Venus were obviously those seen indistinctly in ultraviolet photographs from Earth. These comparative photographs show how the gross horizontal Y-shaped marking seen from Earth is resolved into the intricate pattern of the Mariner picture on the right.



ultraviolet light. Robert Strom of the University of Arizona's Lunar and Planetary Laboratory compared a handful of photographs of Venus taken by Earth-based telescopes with the new Mariner 10 pictures. "These Mariner pictures exceed our greatest expectations," he exclaimed, and then added that the new pictures would let astronomers view the Earth-based pictures from an entirely different standpoint. "Now we will be better able to understand what it is we see from Earth," he said.

In the Video Analysis Facility, Verner E. Suomi, a specialist in satellite meteorology of the Earth, peered through stereo viewers at the cloud pictures of Venus, seeking the three-dimensional effects that would enable him to measure cloud velocities. A major question was why the atmosphere of Venus, as observed in ultraviolet light, rotates so fast compared with the planet itself: in four days compared with 243 days for the planet.

One suggestion which quickly arose was that solar heating of equatorial regions produces a local wave in the atmosphere that gives rise to a circulating equatorial current. And since hot equatorial air will also tend to move to cooler regions, there is a spiraling speedup of the atmospheric currents at higher planetary latitudes. Transverse bands could be seen across the Venus cloud streams, which Dr. Suomi likened to bands across streaks of cirrus clouds in Earth's skies, but on a much larger scale. He pointed to cellular structures in the Venus clouds, each some 200 to 300 km (125 to 185 mi) across.

Although the spacecraft had performed well, Gene Giberson, Mariner Project Manager, admitted to several anxious moments when interviewed just after the encounter. Twenty minutes of finger crossing occurred when Mariner 10 passed closest to Venus and was aligned in space by the star sensor locked on Canopus. At any moment, glare from the brilliant Venus might have caused the spacecraft to turn around, thereby swinging the cameras and other instruments away from Venus at this critical time. Giberson explained that this calculated risk had to be taken since project management could not risk a potentially disastrous gyro malfunction during the flyby of Venus.

The decision to make the encounter with the star sensor in control had paid off; Mariner 10 kept its lock on Canopus and provided a very steady platform for the photographs and other experiments. The final picture of Venus was taken on February 13, 1974, bringing the grand total to 4165 images of the cloud-shrouded planet. Much had been learned during the encounter to supplement earlier observations of Venus from spacecraft and from the Earth.

As Mariner 10 sped toward Venus from the planet's night side, the spacecraft's instruments observed how Venus disturbs the magnetic field in interplanetary space and the flow of charged particles—electrons and protons—from the Sun, known as the solar wind. Venus causes a tail-like disturbance in the solar wind's charged particles, stretching behind the planet away from the Sun. At the same time, Mariner's magnetometer found that the magnetic field in space was twisted by the presence of Venus so that it pointed toward the planet along the tail of charged particles.

But Venus's magnetic field, which is less than one-twentieth of one percent of Earth's field, is insufficient to deflect the solar wind as Earth's field does. This very small and irregular magnetic field is insufficient also to trap stable populations of particles such as found in the radiation belts of Earth and Jupiter. Yet Mariner 10 showed that the solar wind is greatly modified by the presence of Venus. This effect was particularly noticeable because, for at least three days prior to and during the encounter with Venus, general conditions in interplanetary space were unusually quiet.

Mariner 10 confirmed the earlier findings of Mariner 5 and Venera 4, which had discovered a bow shock—a wave in front of the planet like the bow wave of a ship in water. Somehow the ionosphere of Venus forms this bow shock in the solar wind and stops the wind from plunging directly into the atmosphere of the planet. How and why this bow shock occurs is not fully understood. The charged particle experiment did not detect any high-energy protons or electrons within the bow shock, up to several Venus radii downstream.

Certainly the effect is very different from that on Earth, Moon, Mars, and Jupiter. The Venus bow shock might be a direct interaction of the solar wind with the atmosphere of Venus, or with just the ionosphere. It may alternatively arise because the solar wind induces magnetic fields and produces thereby a pseudo, or false, magnetopause, as though Venus had a magnetic field like the Earth.

The temperature of the clouds of Venus was measured from infrared radiation emitted by them, using the radiometer carried by Mariner. As expected from other measurements, there was no detectable difference in the 250 K (-9°F) temperature of the cloud tops between day and night. Reduced infrared radiation near the edge of the visible disc of Venus confirmed that the atmosphere is very opaque.

The UV airglow spectrometer measured the amount of ultraviolet emitted by Venus's upper atmosphere to seek important gases there. One of these gases, hydrogen, is believed to control the chemistry of the planet's atmosphere, forming sulfuric acid clouds and water vapor droplets. Were Venus to lose its hydrogen, the dense, heat-gathering atmosphere of carbon dioxide might be rapidly dissociated by sunlight into carbon monoxide and oxygen, with significant changes to the planet's heat balance.

Mariner 10 confirmed the presence of hydrogen and, even more important, obtained evidence that indicates that it originates at the Sun. If the hydrogen originated from the chance impact of a comet with Venus, as might have happened, deuterium (heavy hydrogen) would also be expected, but because Mariner 10 found no deuterium on Venus, scientists conclude that the hydrogen comes from the solar wind, which has virtually no deuterium. So the hydrogen on Venus will be replenished as long as the solar wind blows.

Mariner 10 also detected small quantities of helium on Venus, but 10 times as much atomic oxygen as on Mars. This high concentration of atomic oxygen suggests that, contrary to conditions at Mars, the upper atmosphere of Venus, where sunlight splits oxygen molecules into atoms, does not mix with lower layers. This lack of mixing seems also to be evidenced by the limb photographs, which show a distinct flat-topped atmosphere of clouds surmounted by several tenuous horizontal layers (Fig. 6-6).

By observing radio signals coming from Mariner 10, scientists determined how the gravity of Venus pulled the spacecraft, and hence they were able to clarify some of the physical properties of Venus. They found that Venus is 100 times closer to being a perfect sphere than is Earth. Radio waves passing through the Venus atmosphere as the spacecraft went behind the planet showed that a lower cloud layer which rises from 35 to 52 km (22 to 32 mi) above the planet's surface consists of quite different clouds from the higher

Fig. 6-6. Meanwhile, early pictures were being enhanced by the computer to show several distinct layers of limb haze. This picture was obtained in orange light 15 min after closest approach on February 5. The thickness of the haze above the visible clouds is about 6 km and appears to extend over the whole planet.

cloud deck. The highest deck extends 60 km (37 mi) above ground level. This upper layer is thin, broken, and rapidly moving, as contrasted with the thick and probably unbroken lower deck. Four distinct temperature inversions, i.e., places where the temperature increases for a short distance with increasing height, were observed by Mariner 10 at altitudes of 56, 61, 63 and 81 km (35, 38, 39 and 50 mi). They are possibly associated with specific cloud layers.

Mariner also found that the electrically charged particles making up the ionosphere of Venus peak into nighttime layers at 120 and 140 km (75 and 87 mi), whereas a stronger ionosphere in the daytime peaks into a higher layer at 145 km (90 mi). Earth's ionospheric layers by contrast have more layers in daytime than at night.

As mentioned earlier, photographs returned from Venus were at first very disappointing. They showed about as much detail as the top of a thick fog bank. Yet these photos were valuable in that they proved that Venus does have a structureless, hazy, visible surface of clouds down to a resolution of 100 m (300 ft). As Mariner 10 sped from Venus, a special sequence of ultraviolet photographs revealed a complex atmospheric pattern. This pattern had been photographed in

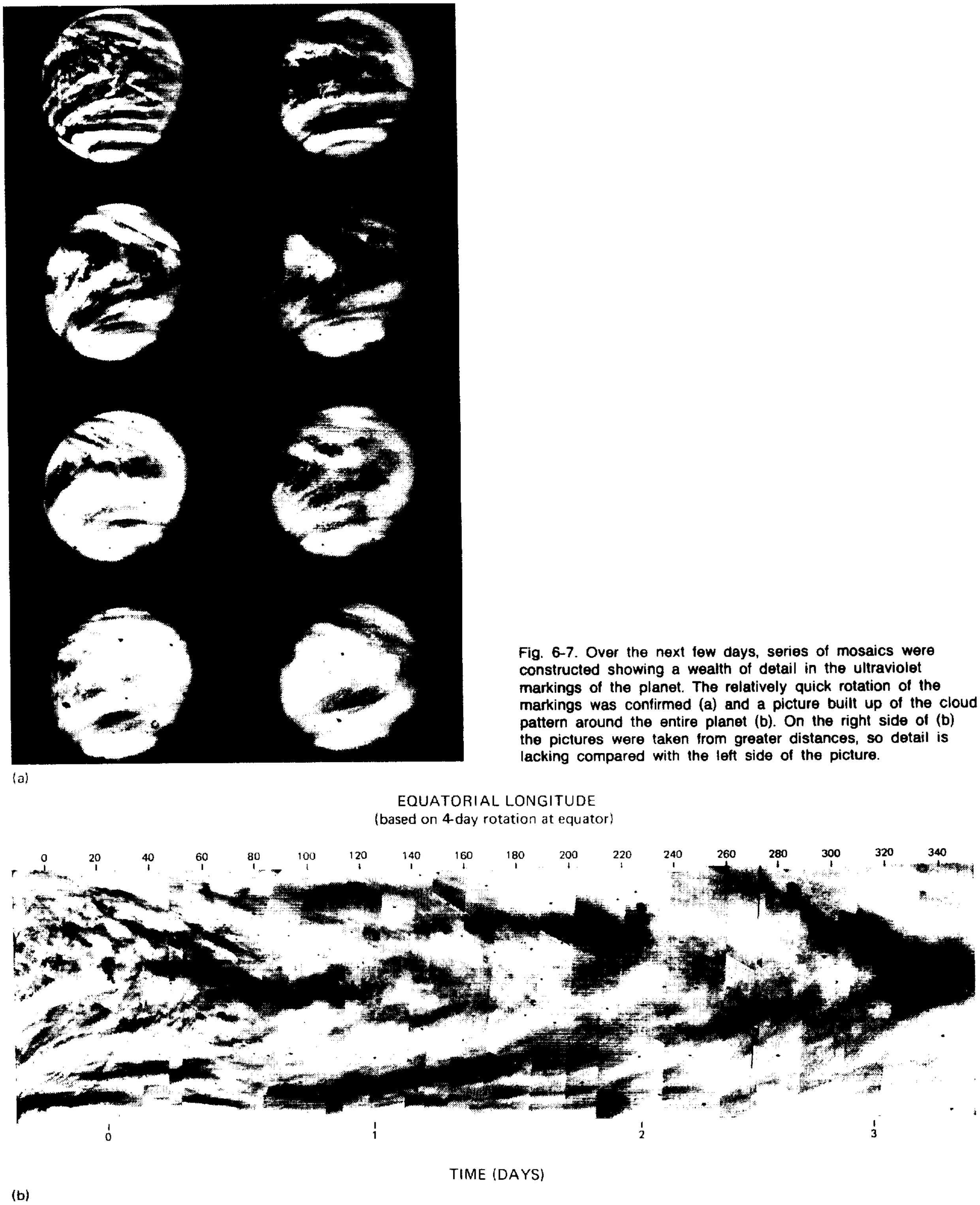


Fig. 6-7. Over the next few days, series of mosaics were constructed showing a wealth of detail in the ultraviolet markings of the planet. The relatively quick rotation of the markings was confirmed (a) and a picture built up of the cloud pattern around the entire planet (b). On the right side of (b) the pictures were taken from greater distances, so detail is lacking compared with the left side of the picture.

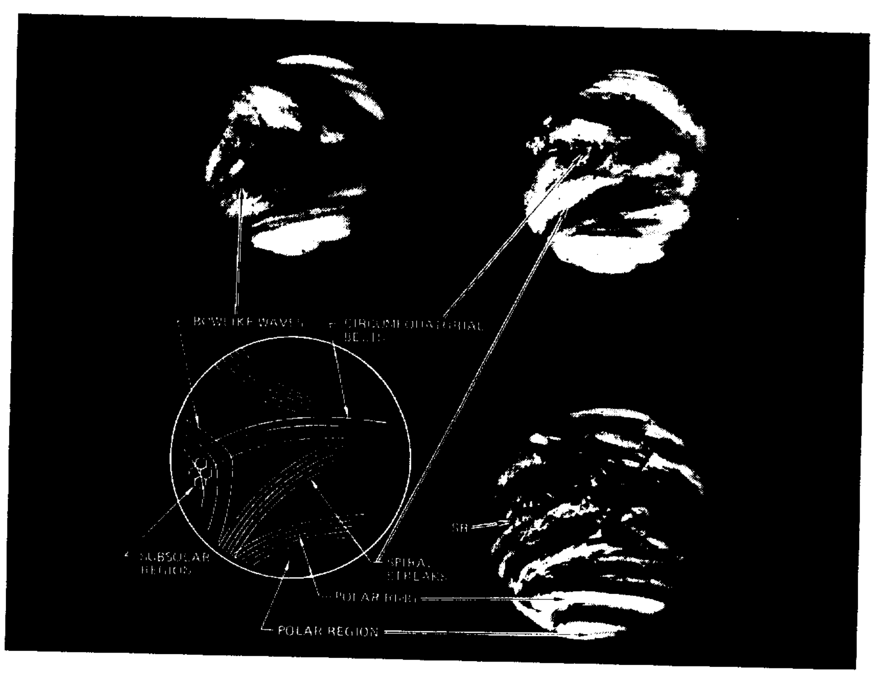
gross detail from Earth. Now Mariner 10 revealed its intricacies (Fig. 6-7).

At the point on Venus where the Sun shines from directly overhead, rising cells of air take on polygonal shapes. Larger cells have dark edges and intricate internal structure. They cause an area of planetary disturbance surrounded by great waves of atmospheric ripples, like those from a stone thrown into a pond, but on a scale of many hundreds of miles (Fig. 6-8).

Along Venus's equatorial zone are fine streams of clouds—faint but quite distinct (Fig. 6-9). Y- and C-shaped markings, prominent on Earth-based ultraviolet photographs, are revealed as consistent markings, a spreading pattern of clouds opening in the direction of rotation. Their motions are clearly shown in time-lapse motion pictures made from the individual photographs obtained from Mariner showing several planetary rotations of the cloud patterns. Both polar regions have hoods of clouds with spiral patterns between the hoods and the equatorial regions. These cloud patterns, which would be quite invisible to the eye of an astronaut orbiting Venus because they are only visible in ultraviolet light, can be interpreted by two extreme theories. One is that solar heating develops cloud patterns without large-scale motions of the atmosphere itself. The other is that solar heating actually drives large masses of air from the equator to the poles, accompanied by undercurrents back from the poles to the equator. Which theory is closer to the truth requires further studies of the photographs, probably assisted by results from a later Pioneer Venus mission to the cloud-shrouded planet planned by NASA several years after Mariner 10.

Fig. 6-8. Close-ups, such as this picture taken February 6, 1974, from a distance of 790,000 km (490,000 mi), revealed cells of rising air at the subsolar region of Venus.

Fig. 6-9. Scientists were able to identify bowlike waves, equatorial belts, spiral streaks, and the bright polar regions as more and more pictures accumulated.



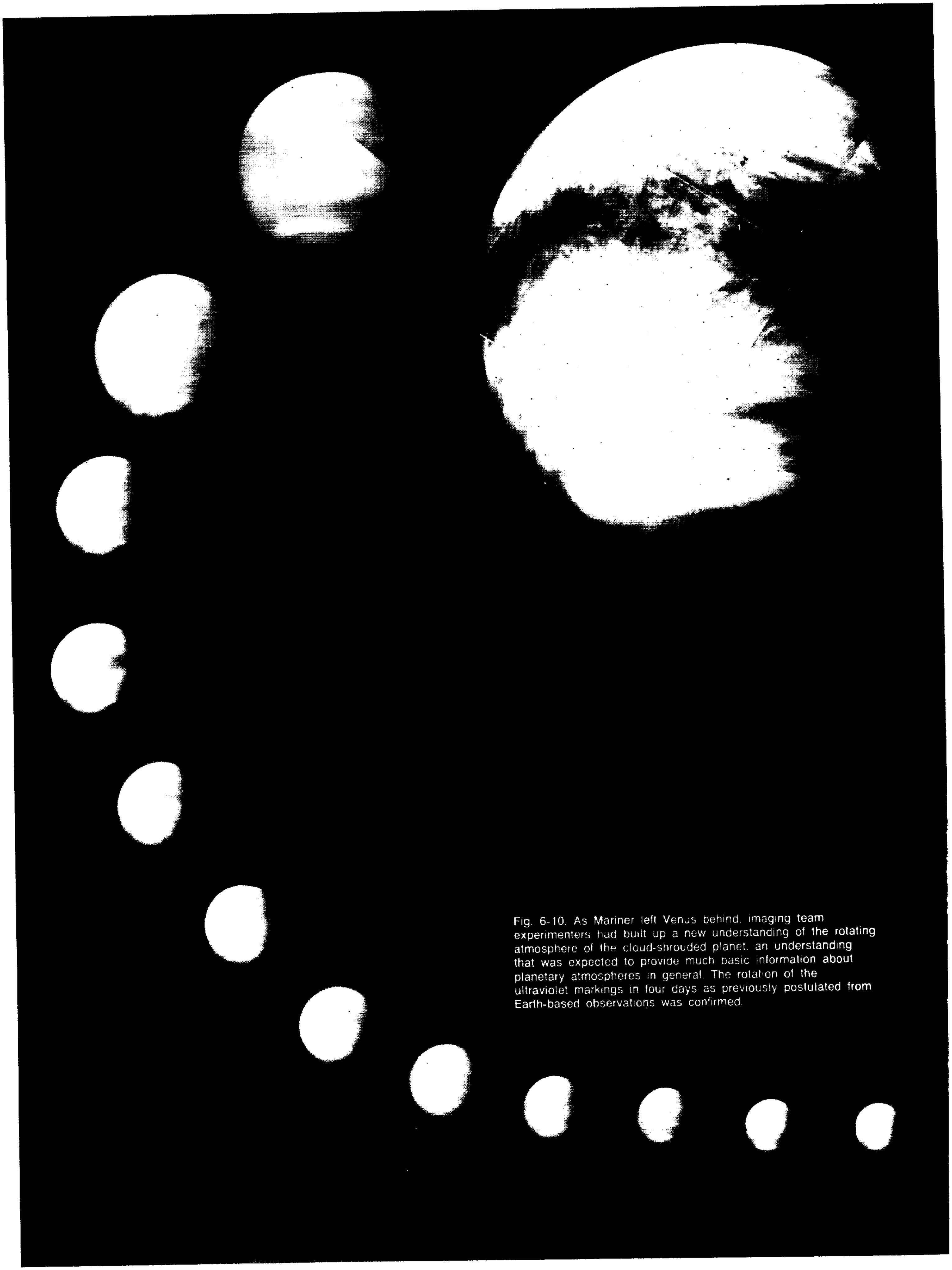
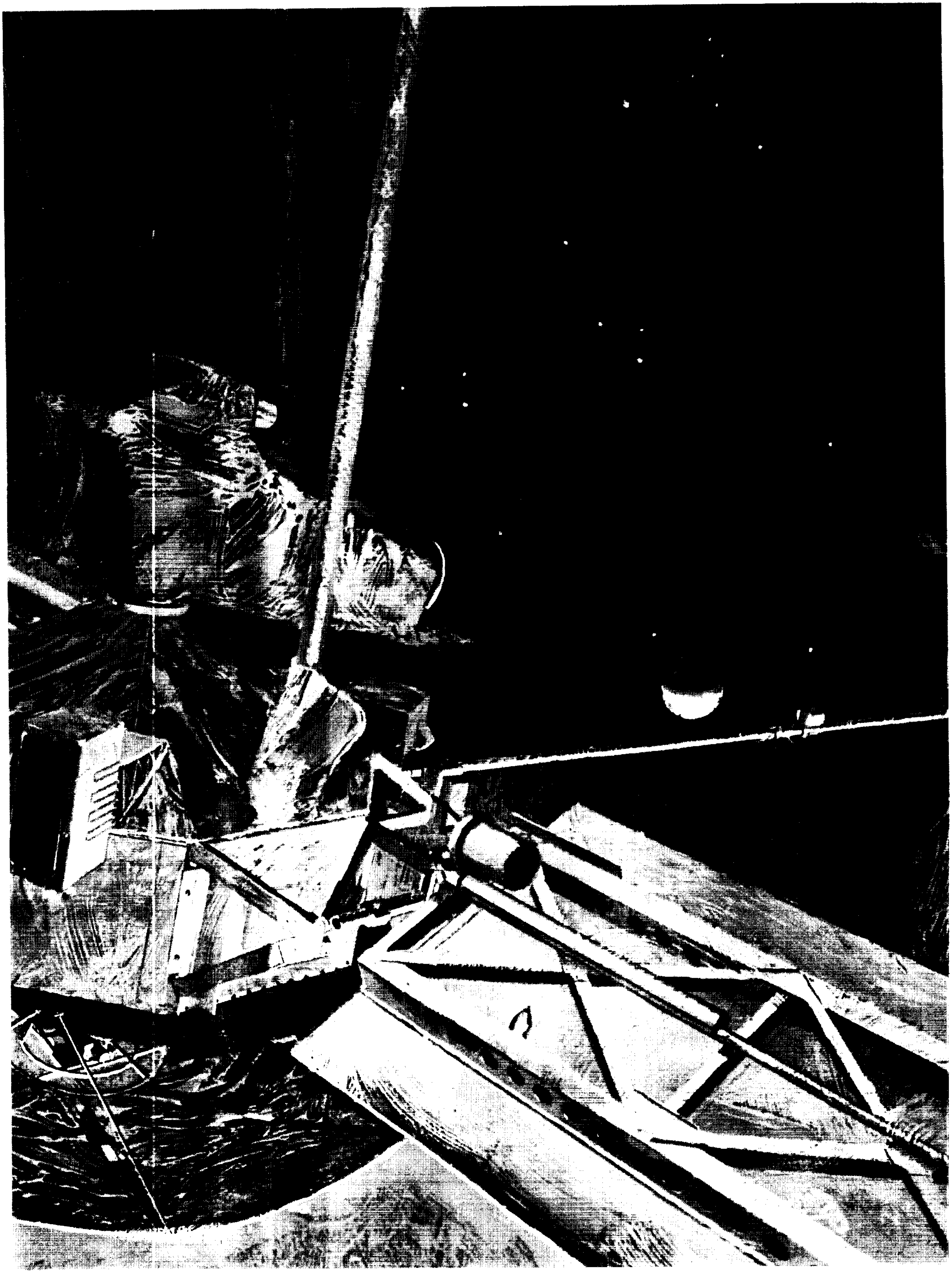


Fig. 6-10. As Mariner left Venus behind, imaging team experimenters had built up a new understanding of the rotating atmosphere of the cloud-shrouded planet, an understanding that was expected to provide much basic information about planetary atmospheres in general. The rotation of the ultraviolet markings in four days as previously postulated from Earth-based observations was confirmed.



Chapter 7

Mercury, Moonlike and Earthlike

AS MARINER'S CAMERAS snapped the last pictures of Venus, the thoughts of the scientists and engineers turned toward the mission's priority target—Mercury. Forty-three days of cruise and a third trajectory correction maneuver remained before mission completion. Analysis of the failures and anomalies experienced to date continued at an urgent pace, while at the same time the complicated Mercury science sequences were subjected to detailed scrutiny in search of adjustments required to accommodate the corresponding changes in spacecraft performance.

A Troubled Journey

About one week after Venus encounter, a decision had to be made as to how the spacecraft should be redirected toward Mercury with the least expenditure of maneuvering gas.

The oscillation problem and the attendant risk of losing all attitude-control gas if there should be a loss of celestial reference resulted in a number of changes in mission operations. One was the cancellation of further roll calibration maneuvers; another was the introduction of a period of "solar sailing" during which the spacecraft roll, pitch, and yaw axis rates and limit cycle magnitude were reduced by differential tilting of the solar panels to use the pressure produced on the panels by solar radiation pressure in a controlled manner, like wind on a sail. This technique significantly reduced the amount of gas which would have been used in the standard celestially controlled cruise mode.

On February 14, 1974, Mariner's gyros were tested preparatory to making the third trajectory correction maneuver. The gyros did not oscillate during the first two tests, but did so during the third test and during a commanded turn of the spacecraft. As a result, the planned trajectory correction maneuver was cancelled; it would have caused the loss of too much gas in gyro oscillations. Instead, a Sun-line maneuver was decided upon, to be executed in mid-March. At that time the position and orientation of the spacecraft would be such that the normal position of the rocket engine, relative to the Sun and Canopus, would be suitable to apply the right amount and direction of thrust to change trajectory without requiring the spacecraft to roll or pitch to do so. By making the trajectory change in this way, project personnel would be able to send Mariner to rendezvous with Mercury at the correct point on the dark side on March 29, but approximately 17 min later than the time desired. All the science data originally planned for Mariner to gather at Mercury could still be obtained.

Shortly after midnight, in the early morning of February 18, duty operators were startled to observe from the telemetered data that Mariner 10 had lost celestial reference on the star Canopus. During the next three hours, project staff members rushed to JPL and watched helplessly as Canopus "drifted" through the star tracker's field of view twice and the spacecraft gyrated in short gyro-off/gyro-on cycles. A normal roll search for Canopus could not be started until communications were reestablished between the spacecraft and a big ground antenna; Mariner had been in communication with a 26-m (85-ft) antenna at the time of the trouble. After a big (64-m) antenna had been obtained for the troubled spacecraft, a command was sent to initiate a roll search, and Canopus was acquired 1.3 min later. The gyros had been on for 1 hr and 48 min, but fortunately no oscillations were observed until the final acquisition of Canopus. Approximately 70 millipounds of nitrogen gas were lost because of this incident, which was thought to have been caused by a bright particle passing the spacecraft. The occurrence of bright particle distraction had increased from a rate of 1 or 2 a week immediately after launch to about 10 a week by the end of February. On March 6, a group of bright particles again disturbed the star tracker and caused the spacecraft to roll and waste attitude control gas for 40 min.

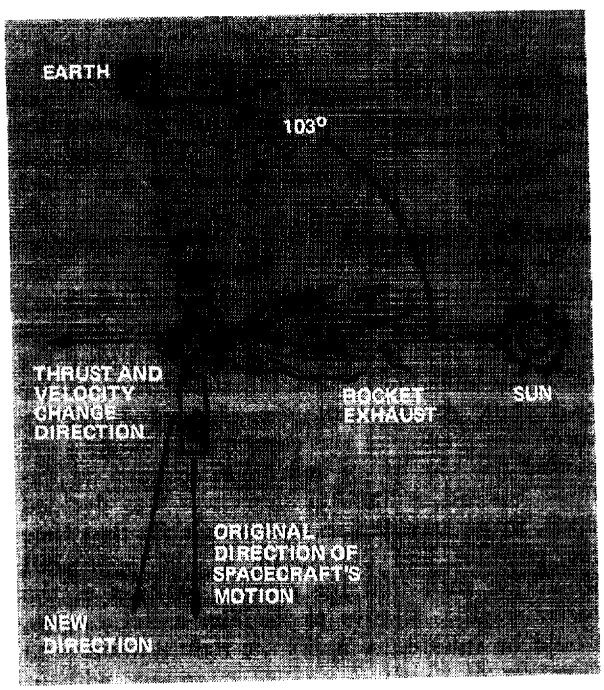


Fig. 7-1. Described as a "trick maneuver" because it had to be done at a particular time, TCM-3 was a Sun-line maneuver to aim the spacecraft for Mercury encounter. It became necessary to do it this way because the spacecraft had encountered problems in its orientation system. This maneuver was made when the spacecraft reached the orientation in space at which the rocket engine could be fired without the necessity of rolling the spacecraft to direct the thrust of the rocket.

On March 13, the project staff held a final conference to approve the Sun-line course change. On March 16, at 04:54 a.m. PDT, the propulsion system was ignited and burned for 51 sec to change the velocity of Mariner by 17.8 m/sec (59 ft/sec) directly away from the Sun. This would change the Mercury flyby from the sunlit to the dark side of the planet (Fig. 7-1). The aim point had been carefully chosen to get the best possible science data and also to allow a return to Mercury six months later.

Conditions were now very critical. Because the angle between the velocity change due to the trajectory correction maneuver and the line between spacecraft and Earth was 103 deg, the doppler shift measured at Earth would show only a small component. So no precise estimate of how successful the maneuver had been could be obtained until tracking data had been analyzed for about 10 days after the maneuver. This might be too late to make corrections and still reserve sufficient gas for a second encounter with Mercury. Another possibility was to use the high data rate engineering telemetry to measure the pressure within the rocket thrust chamber and use this to determine the actual magnitude of the velocity change produced by the rocket thrust. If the engine burned too "hot," there would be an overshoot that could not subsequently be corrected by a Sun-line maneuver. If, however, the engine burned "cold," the undershoot could be corrected by a further firing of the rocket engine within 24 to 48 hr.

The rocket engine fired by command as scheduled. Preliminary analysis using data gathered from the engineering telemetry supplemented by the doppler shift measurement indicated that the maneuver had been about one percent short of that required. Thus the flyby was expected to be 200 km (124 mi) closer to Mercury than planned. Since this still satisfied all the requirements of the science experiments at Mercury, no additional maneuvers were planned.

Historic Encounter

On Sunday, March 17, the day after the maneuver, the nonimaging science experiments were turned on in preparation for the encounter. All instruments were checked and confirmed to be in excellent operating condition. A little less than one week later the first TV image of Mercury was displayed on screens at JPL. By now the high-gain antenna had mysteriously recovered (never to fail again, as it turned out), and high-resolution full coverage of Mercury was expected.

First pictures of Mercury were about the same as pictures obtained from Earth, but gradually, as more pictures came back from the spacecraft, observers could distinguish bright spots which had apparent diameters up to 400 km (250 mi) (Fig. 7-2). Some of the bright spots lined up with light streaks to merge into great circle arcs like the bright rays on the Moon.

By March 25, the pictures showed a surface of mottled character, suggestive of a fuzzy picture of a cratered surface such as Earth's Moon (Fig. 7-3). Mercury appeared as a wide crescent as Mariner 10 approached. By this time, Mariner was 3.5 million km (2.17 million mi) from

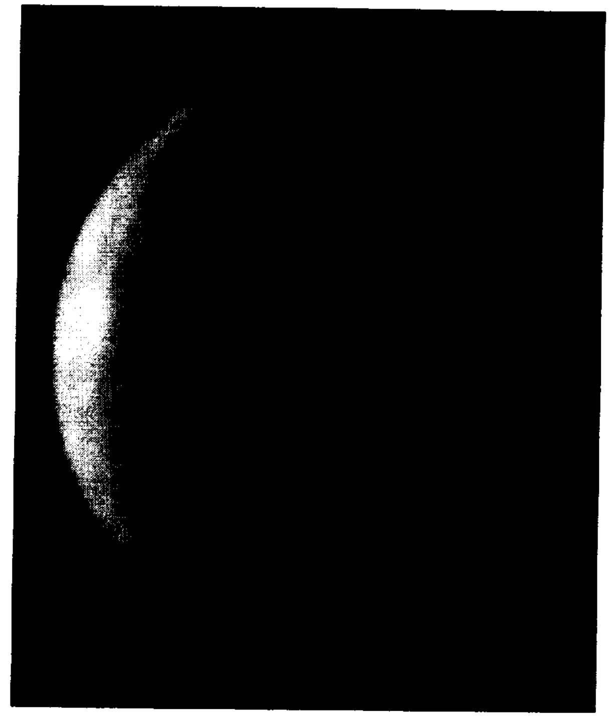
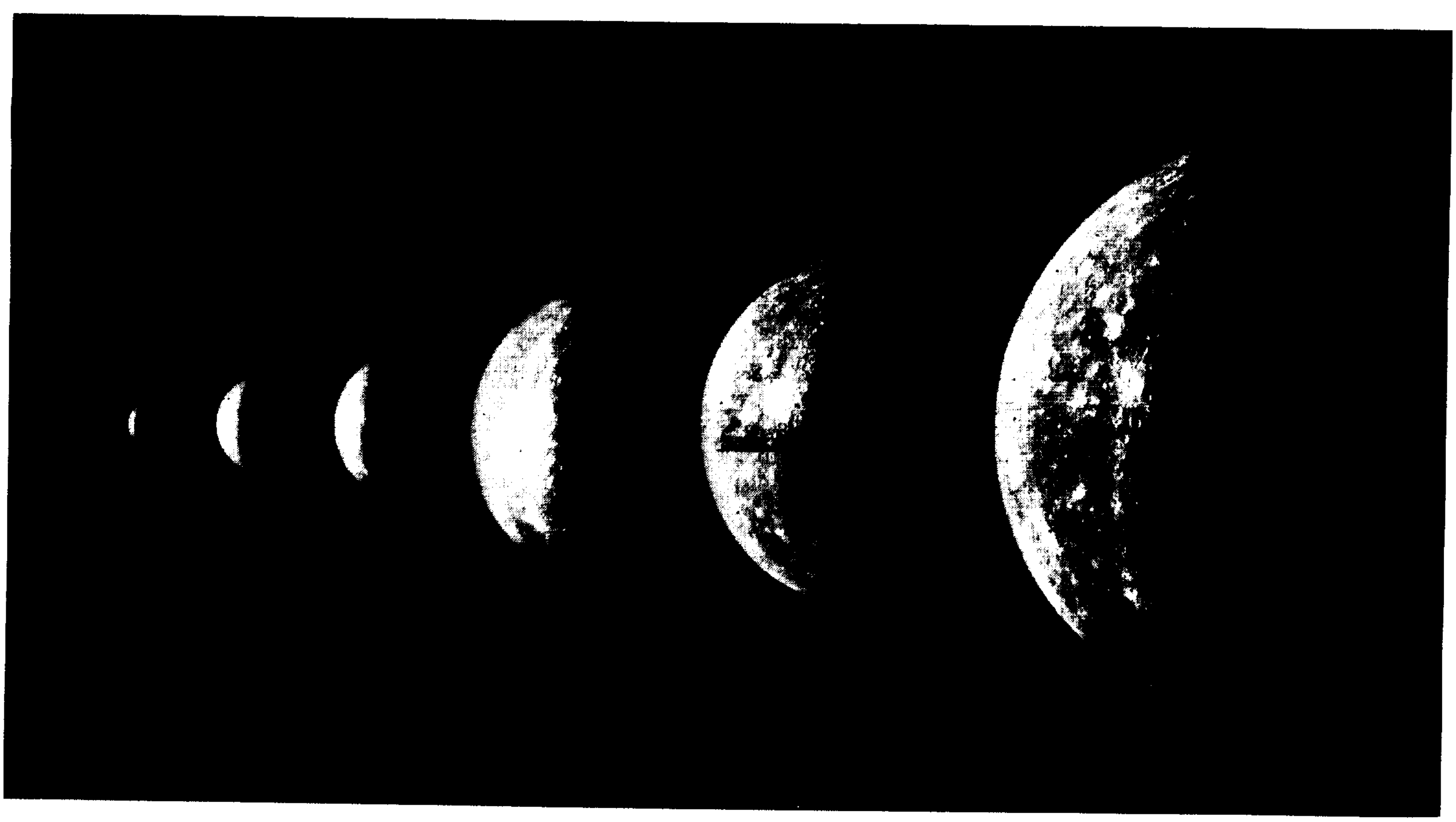


Fig. 7-2. The first pictures of Mercury, like this taken March 24, 1974, at a distance of 4,300,000 km (2,700,000 mi), looked much like Mercury as seen in a telescope from Earth.

Fig. 7-3. But as Mariner continued to bear down on its target, more and more details appeared.



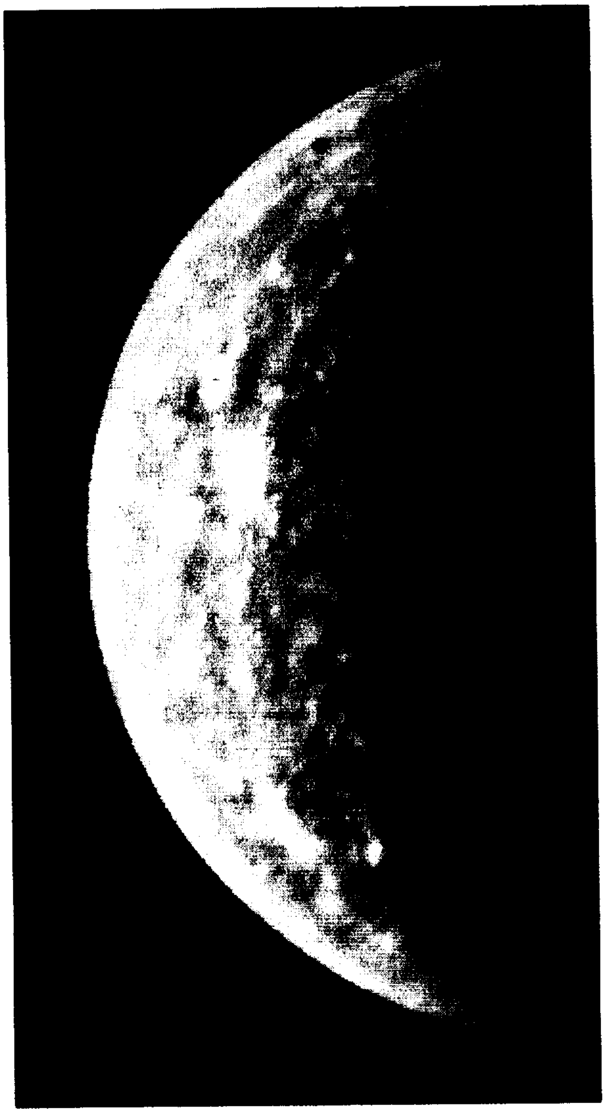


Fig. 7-4. Soon craters on Mercury were positively identified for the first time. Many astronomers had suggested that Mercury would be cratered like the Moon. This computer-enhanced view was taken March 27 from a distance of 1,840,000 km (1,141,000 mi). Craters as small as 160 km (100 mi) across can be made out along the right edge of the crescent, where the Sun is setting on the planet. North is at the top.

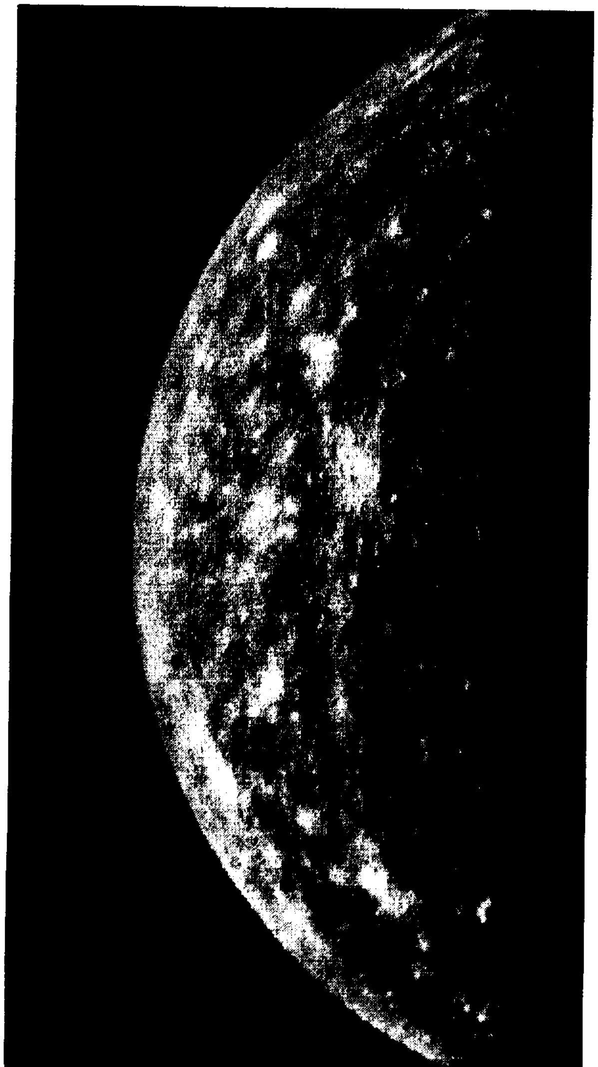
Mercury, and the images of the planet (Fig. 7-4) exceeded the highest resolution previously obtained by Earth-based telescopes. These and subsequent images soon revealed Mercury to be a Moon-like body, heavily cratered, with large flat circular basins similar to those on the Moon and Mars.

The bright spot which was the first feature seen on Mercury in the earliest photographs was soon recognized to be a small, 25-km (15-mi) bright-rayed crater. (It was later named after the astronomer Gerard Kuiper, who had done so much to encourage lunar and planetary exploration at the beginning of the space age and was a member of the Mariner 10 TV team. Dr. Kuiper had died several months earlier.)

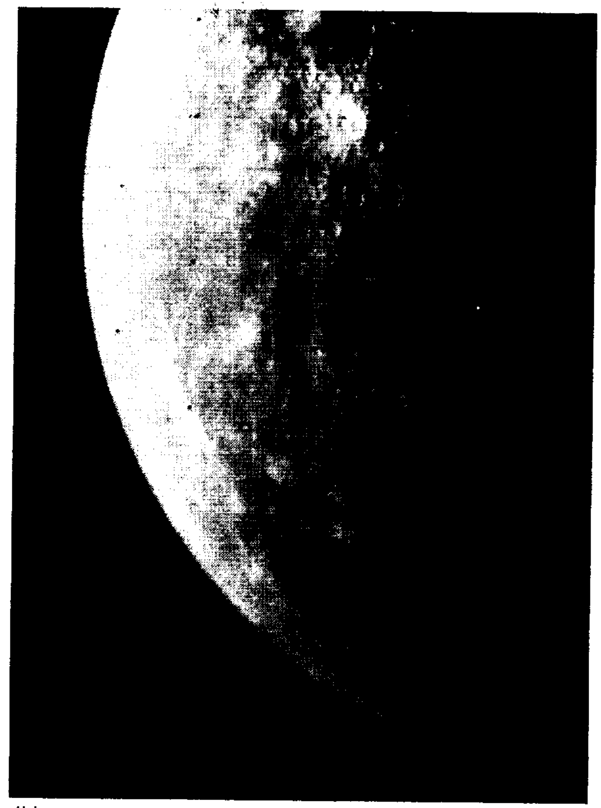
During the next few days the pictures of Mercury progressed from revealing to fantastic (Fig. 7-5). The densely cratered surface showed a profusion of detail. Moonlike, yet at the same time somehow different from the Moon, the face of Mercury was built up in picture after picture. Hurriedly, scientists at the Video Analysis Facility assembled the many photographs into large photomosaics that provided detailed views of almost the whole lighted hemisphere of this small world. As Mariner sent back pictures on leaving Mercury, scientists were excited to find a huge circular feature about 1300 km (800 mi) across located on the terminator. This great basin was surrounded by mountains and with radial structures very similar to the Mare Orientale of the Moon.

Mariner 10 began taking pictures of Mercury on March 23, from a distance of 5.3 million km (3.3 million mi). Photography was intermittent for the next four days but became an almost continuous operation on March 28, one picture being taken every 42 sec. However, Mariner was unable to photograph Mercury during the half hour around closest approach at 1.46 p.m. PDT on March 29, because the flight path had been targeted to pass behind the planet on the night side.

While Mariner 10 was still occulted from Earth by the planet, the cameras started taking pictures of Mercury's far side from the closest possible altitude of about 5790 km (3600 mi). Since the planet blocked radio communications to Earth at that time, the TV frames had to be recorded on tape within the spacecraft for transmission later. Periodic photographic operations continued for another five days until April 3, when the spacecraft was 3.5 million km (2.17 million mi) past Mercury. In all, more than 2000 pictures of Mercury were transmitted from Mariner 10. The



(a)



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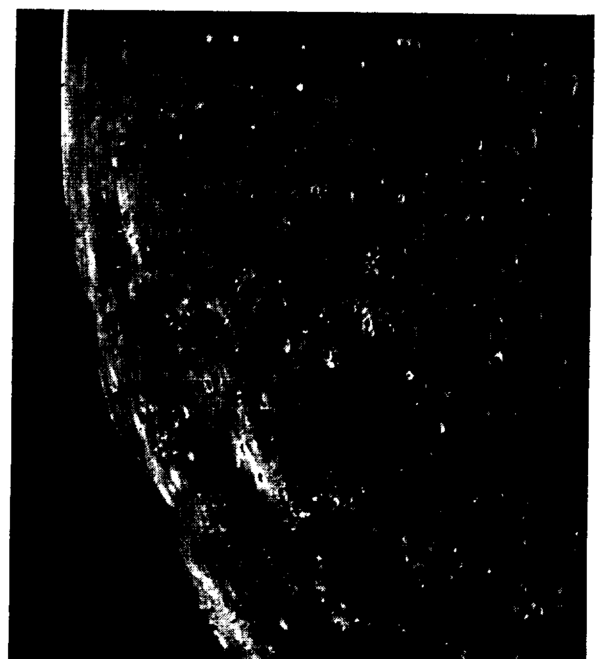
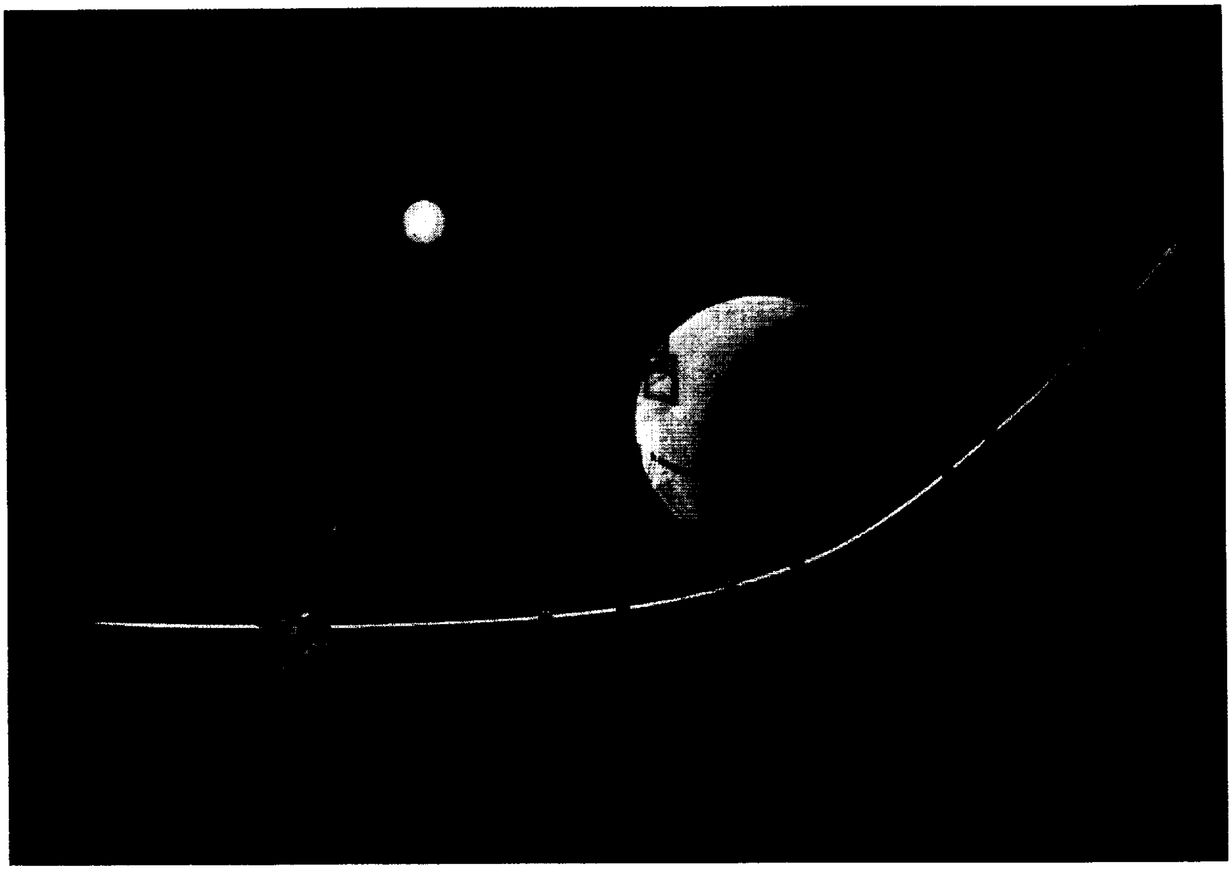


(c)

Fig. 7-5. During the next few hours the details increased. Taken shortly before 12:00 noon on March 28 at 952,000 km (590,240 mi) (a) shows the bright spot between limb and terminator close to the center as a bright-rayed crater. In (b) taken March 29 at 500,000 km (310,000 mi), a lunarlike surface on which features as small as 11 km (6.8 mi) can be seen. The picture no longer shows the whole of the planet. In (c), taken four hours before closest aproach, at 198,000 km (122,000 mi), a profusion of craters in the southwestern quadrant of Mercury can be seen.



(a)

(b)

Fig. 7-6. The Mercury encounter presented problems for the imaging team because flyby would be over the dark hemisphere. The team had to photograph the planet going in to closest approach and then on the outward leg without being able to couple the two sets of pictures together because of limb foreshortening. In (a), an artist's concept of the encounter with Mercury is shown; (b) shows the TV sighting lines shortly before and after closest approach.

photogeometry of the flyby and the angles at which the images of Mercury were obtained are shown in Fig. 7-6.

Mercury had appeared as a fat crescent as Mariner 10 approached the planet (Fig. 7-7). After the spacecraft passed by on the dark side of Mercury, it left in a direction that showed slightly more than half the planet illuminated (Fig. 7-8). Shortly afterwards it was discovered that the Mariner 10 cameras had shown the relative brightness of Mercury and the way the light reflected from the planet is polarized are identical to the Moon.

Fig. 7-7. Two photomosaics were produced showing the view of Mercury on the ingoing and outgoing paths. Eighteen pictures taken at 42-sec intervals were computer-enhanced to make this mosaic. The pictures were taken during a 13-min period when Mariner was 200,000 km (124,000 mi) and 6 hours away from Mercury on 29 March. About two-thirds of the portion of Mercury seen here is in the southern hemisphere.

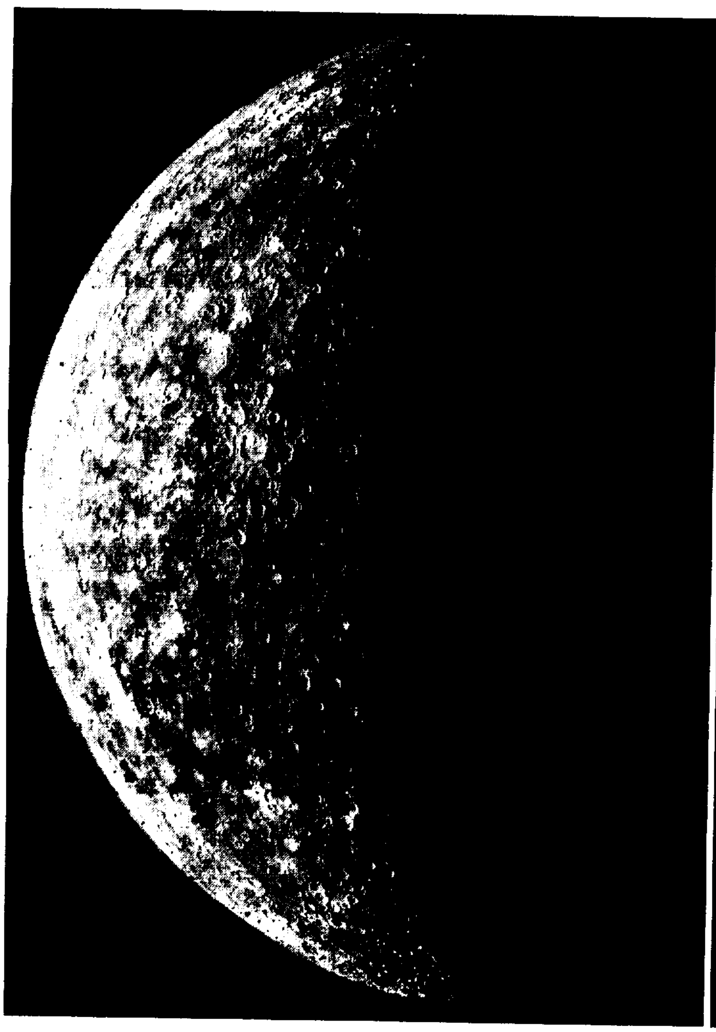
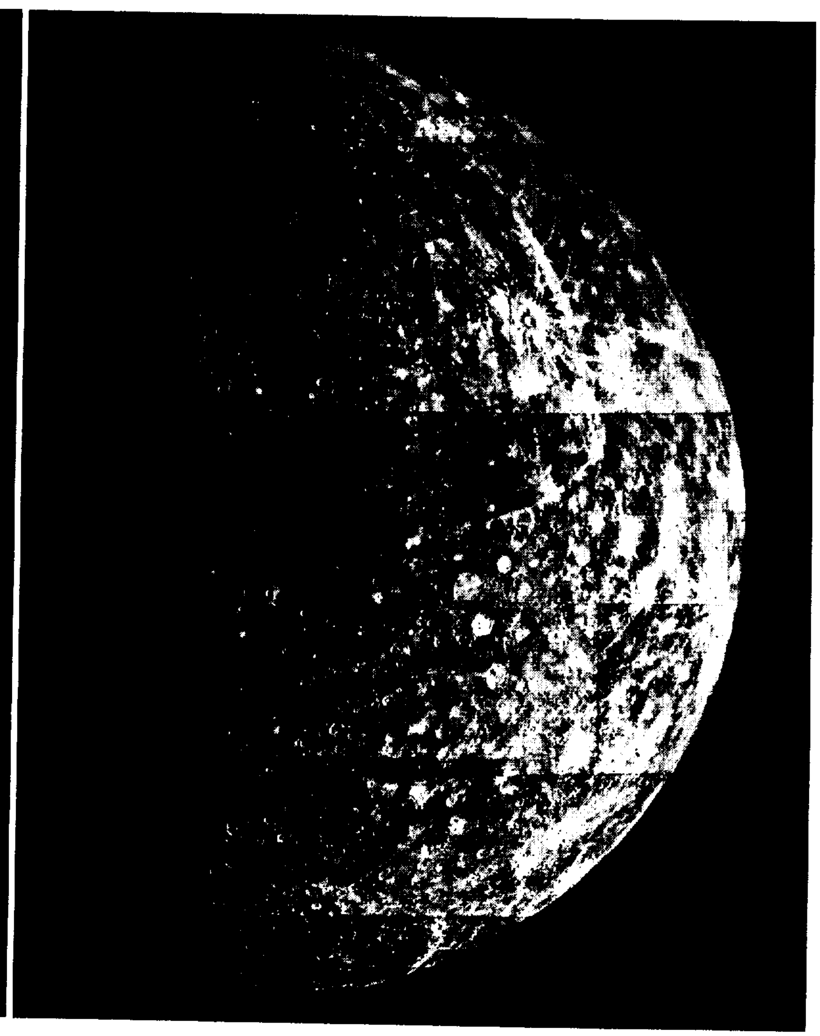
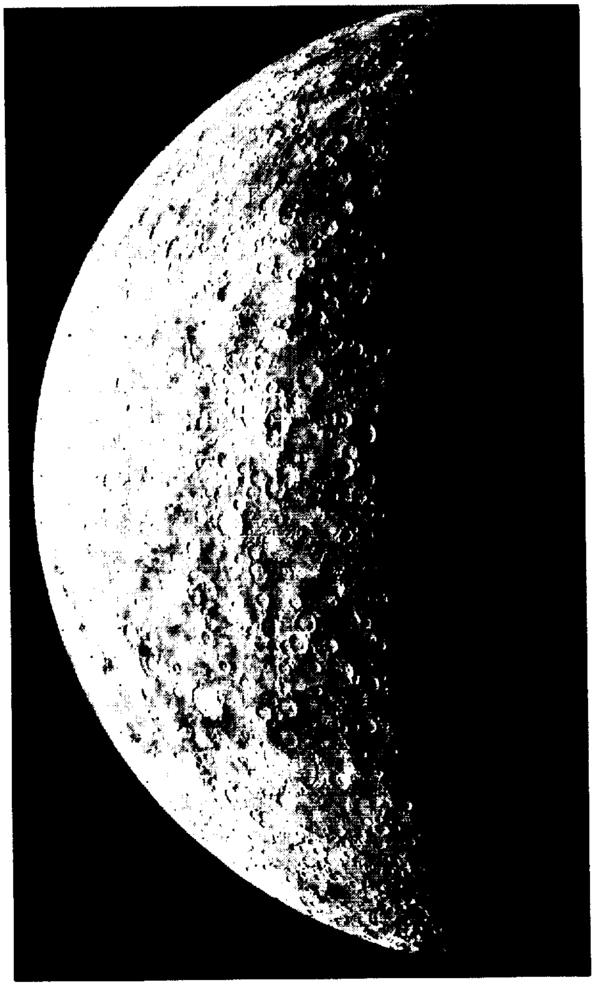


Fig. 7-8. The outgoing mosaic of 18 photographs showed somewhat more of the illuminated surface taken about 6 hours after closest approach. The north pole is at the top, and the equator extends from left to right about two-thirds down from the top.





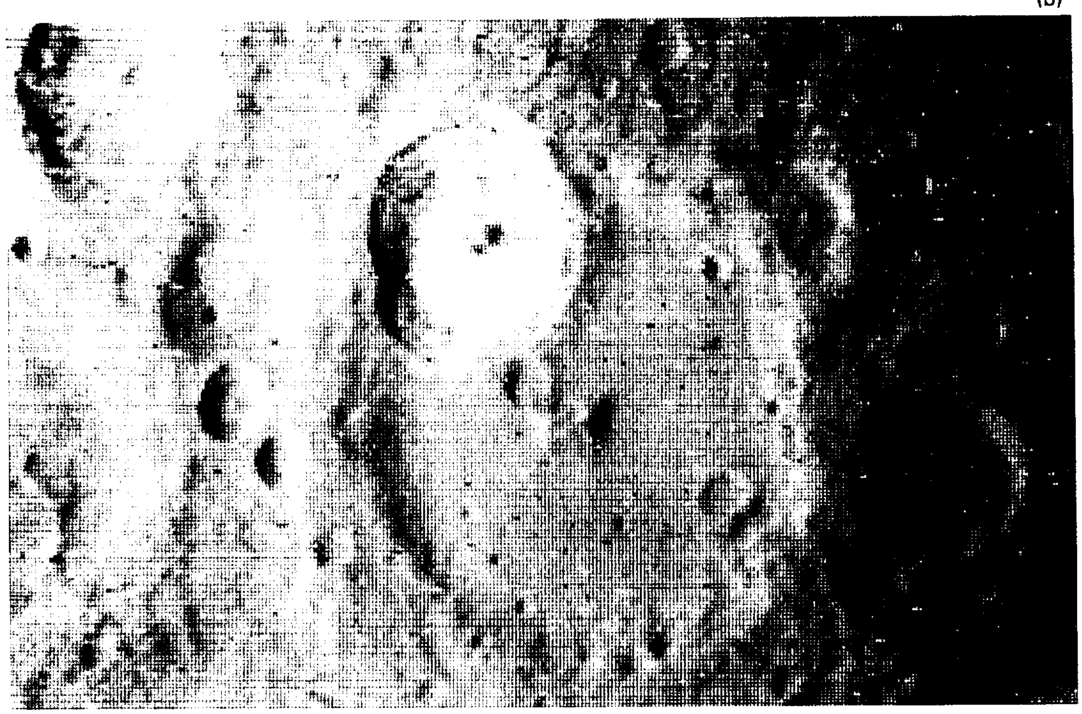
(a)

The brightest crater on Mercury (Kuiper, Fig. 7-9) reflects almost 25% of the sunlight falling on it, just a little more than the brightest feature on the Moon (Aristarchus, Fig. 7-10). Because albedo boundaries between plains and highlands are less clearly defined on Mercury than on the Moon, the planet overall appears of low contrast compared with the Moon.

Photographs of increasing detail revealed that, although generally like the Moon, Mercury has some distinctly nonlunar features (Fig. 7-11) including, for example, large scarps or cliffs nearly 3 km (2 mi) high and stretching as far as 500 km (300 mi) across the surface, which, because of their lobate form, appear to be compressional (thrust fault) features, perhaps resulting from

Fig. 7-9. The bright object was the first feature to be recognized on Mercury and turned out to be a young rayed crater. It was named Kuiper in memory of Dr. Gerard Kuiper, a leading advocate of interplanetary spacecraft and a member of the imaging team for Mariner 10. In (a), the crater is related to the incoming mosaic; (b) shows the crater in close-up as seen at a distance of 88,450 km (55,000 mi) some 2-1/2 hours before closest approach. Kuiper is about 41 km (25 mi) in diameter and is located on the rim of a larger (80-km) and older crater.

(b)



forces on the surface materials as a hot central core of the planet cooled.

The major features of Mercury revealed by Mariner 10's camera were basins, craters, scarps, ridges, lunar-like highlands, and plains. The highlands are cratered about as heavily as their lunar counterparts. The largest basin—named Caloris (the Greek word for "hot") because it is one of the two areas on Mercury that face the Sun at perihelion—is 1300 km (800 mi) across. It resembles the Mare Imbrium basin on the Moon except for an unusual pattern of cracks on its floor (Fig. 7-12). Mercury displays extensive ray systems (Fig. 7-13), similar to those on the Moon, and there are innumerable secondary impact craters, crater chains and great circle alignments of bright features closely resembling lunar ray systems.

Fig. 7-10. By contrast the brightest object on the Moon, the rayed crater Aristarchus, is not quite as bright as Kuiper.

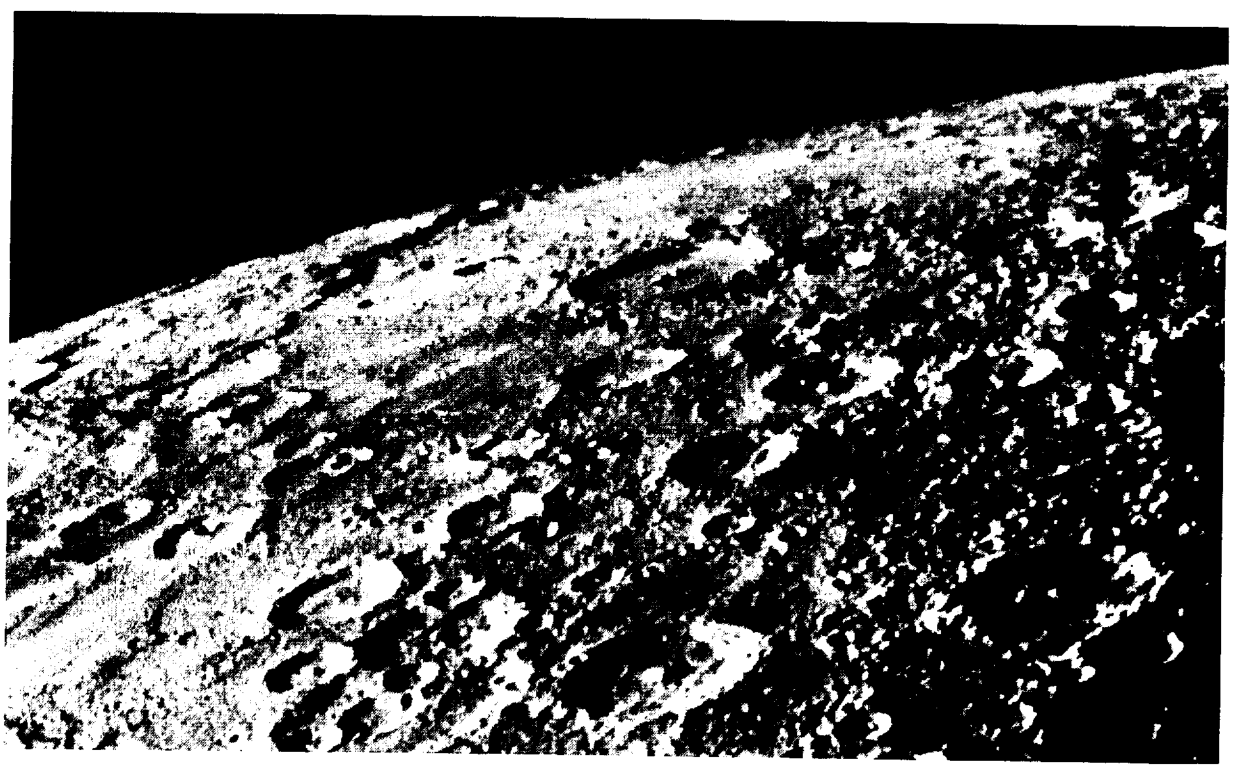


Fig. 7-11. Mariner 10 discovered unusual scarps on Mercury, very different from anything on the Moon. They are believed to be evidence of a shrinking of the planet's crust around its metallic core.

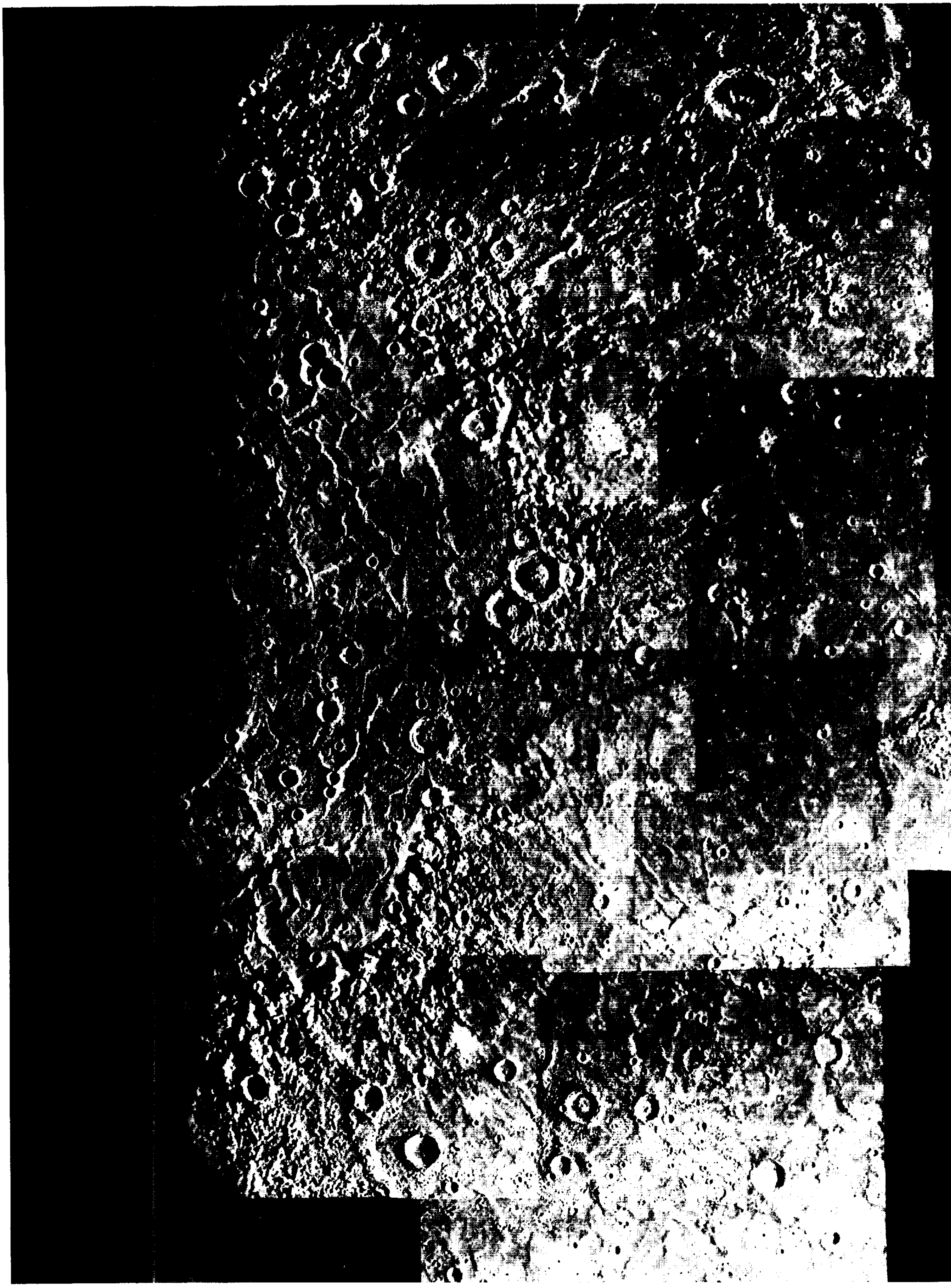


Fig. 7-12. Mariner 10 also discovered a great impact basin on Mercury that is larger than the Mare Imbrium basin on the Moon. It has been named Caloris (meaning hot) because it is located at one of the two spots on Mercury that face the Sun at perihelion, Mercury's closest approach to the Sun.

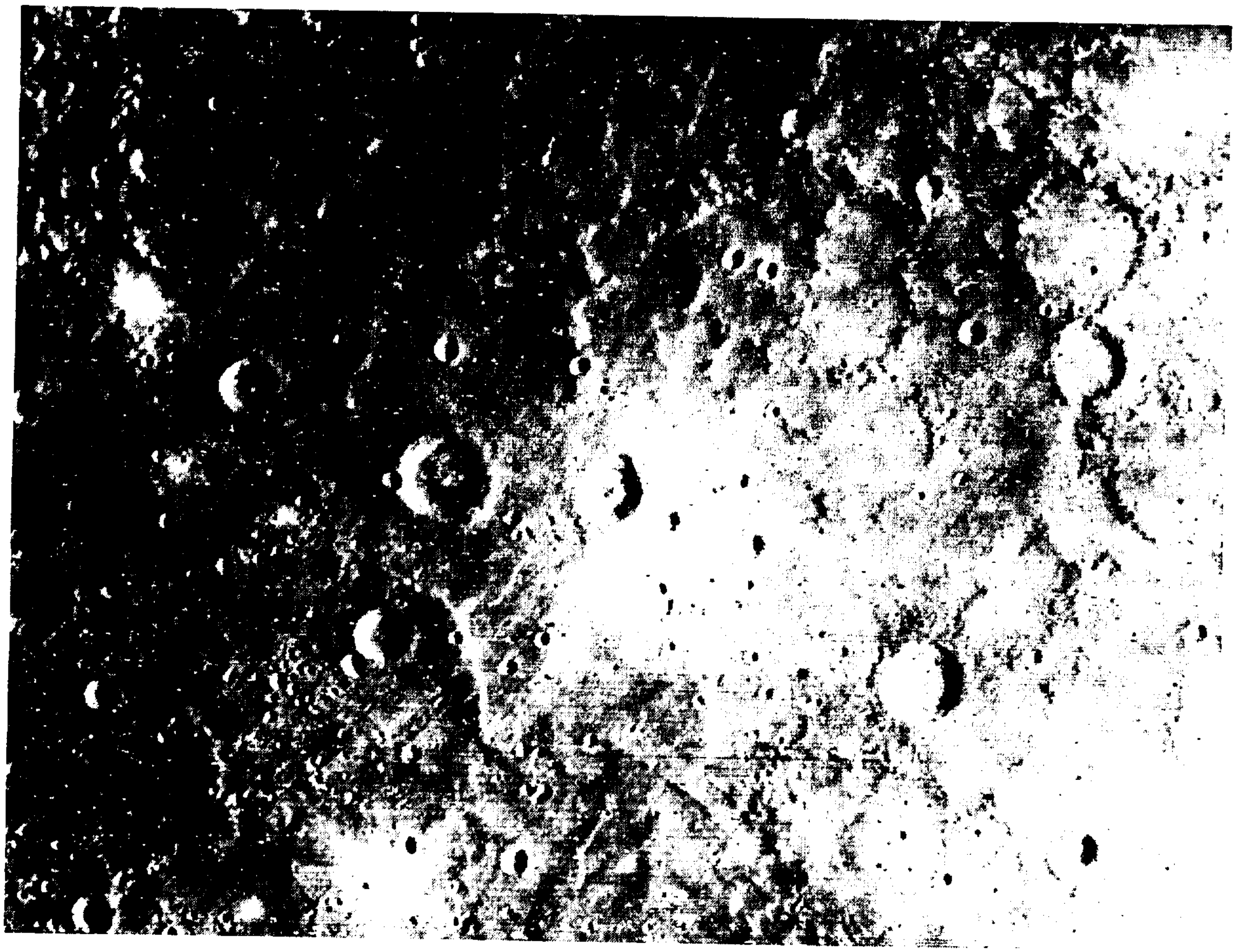
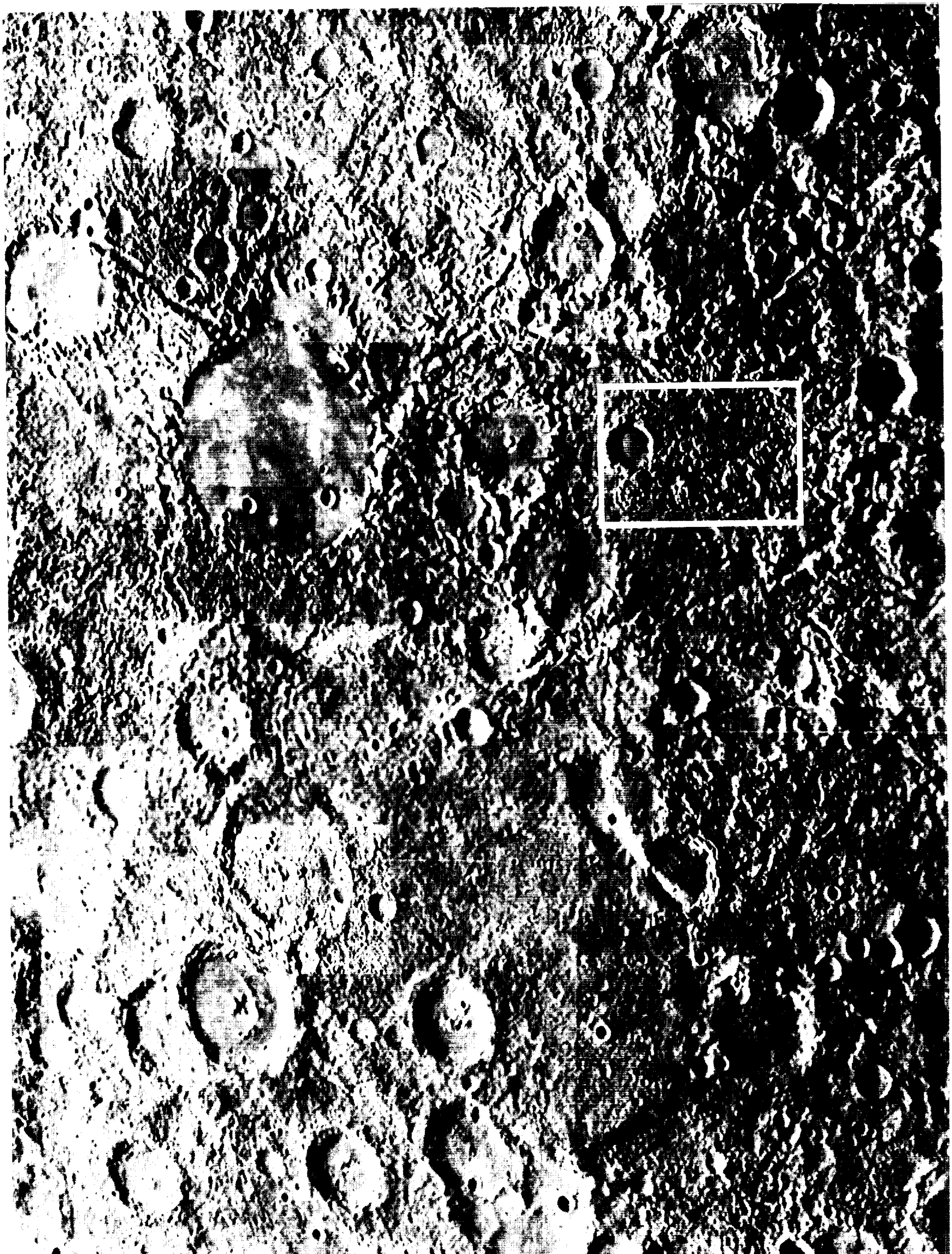


Fig. 7-13. Mercury has many young bright-rayed or haloed craters such as this. They are thought to be similar to the bright-rayed craters of the Moon and to be evidence of the final stages of planetary bombardment.

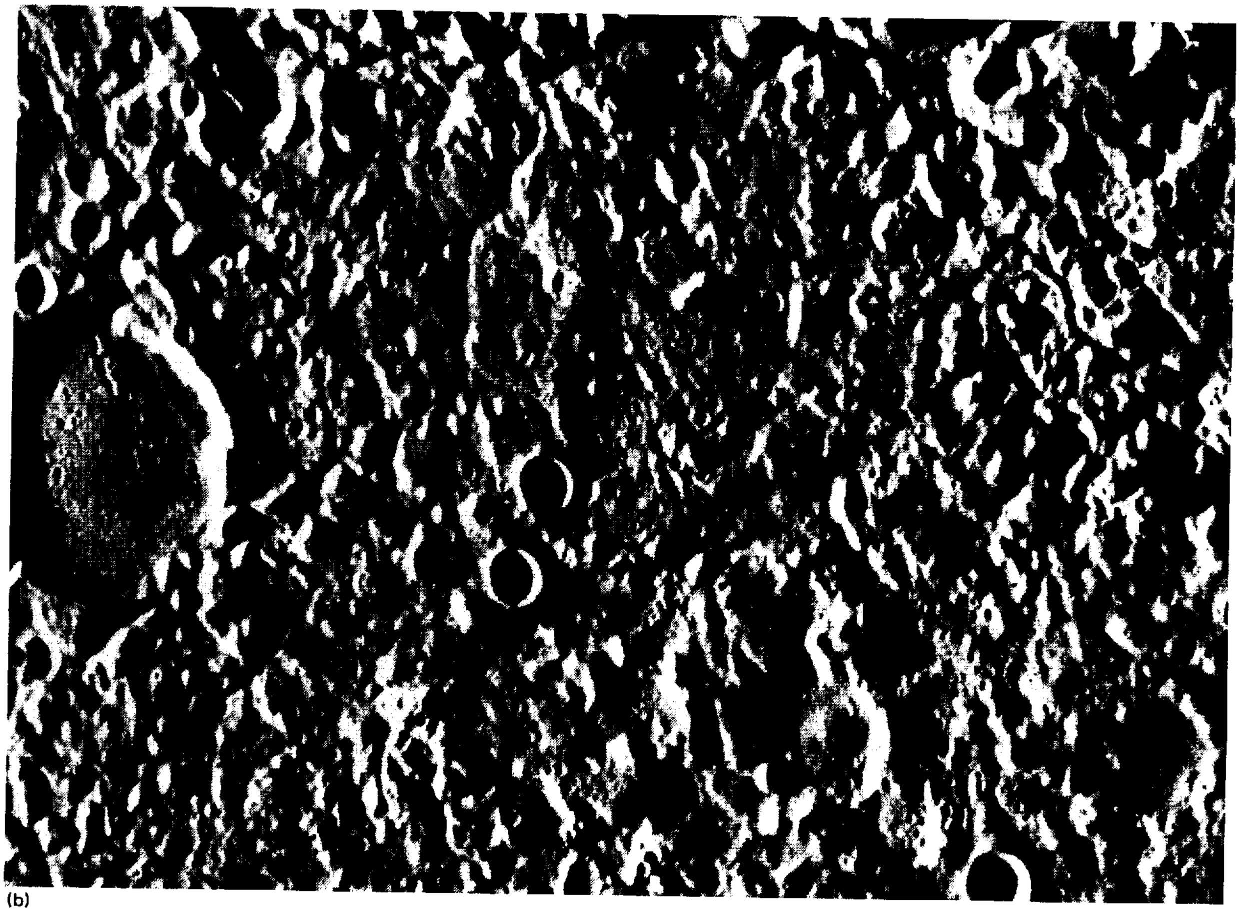
There is also a jumbled terrain (Fig. 7-14), informally termed "weird terrain" by the TV team, which is somewhat analogous to similar areas on parts of the Moon. It is characterized by hills and lineations on which rims of craters are broken and dissected. On the Moon the jumbled terrain is antipodal to the basins of Mare Imbrium and Mare Orientale, believed to be the results of major impacts. On Mercury, it is antipodal to the Caloris Basin, which also is believed to be a major impact basin.

Donald Gault of Ames Research Center has postulated that the "weird terrain" could have been caused by seismic forces transmitted through the body of the planet and along the surface crust, which focussed at the antipodes of the major impact basin.



(a)

Fig. 7-14. Antipodal to the Caloris Basin is a vast area of jumbled, peculiar terrain. It has been suggested that the immense shock waves produced by the impact of the body that produced Caloris were focused around the planet so that the resultant seismic disturbances broke up the surface as shown on this photograph. A close-up of part of this jumbled, peculiar terrain is also shown (b).



(b)

Mare-like surfaces of large extent have now been observed on the Moon, Mars, and Mercury. All show a surprising similarity in the numbers of small craters that pepper them (Fig. 7-15). This implies that all these planets received similar intensities of meteorite bombardment. Prior to the Mariner mission to Mercury, scientists thought that the amount of bombardment might differ at various distances from the Sun. Now it appears that the meteorites were spread evenly throughout the inner Solar System, at least during the final stages of planetary formation.

All the terrestrial planets, including Earth and Venus, may thus have experienced a period of widespread impact cratering and basin formation. The evidence of this process, recorded on the Moon, Mercury, and Mars, has been largely wiped out on Earth and can be demonstrated only by sophisticated geological mapping on ancient surfaces such as the Canadian shield.

By direct computer link through the NASA Communication Center, it was possible to monitor the nonimaging science data being returned from the spacecraft in real-time. The data were processed at JPL and then transmitted to the various principal investigators' facilities at the University of Chicago, Los Alamos Scientific Laboratory, and Goddard Space Flight Center.

This operation permitted continuous data coverage in real-time during critical calibrations and at encounters. It allowed rapid assessment of observations at encounter, which was especially important for the magnetometer and plasma science experiment during this first encounter with Mercury.

Magnetic measurements made in the vicinity of Mercury produced an unexpected and surprising result. Mercury's effect on the solar wind revealed the presence of a planetary magnetic field about one-sixtieth of Earth's field. This field produces a bow shock and fills the plasma cavity expected behind an airless small body like Mercury. The source of the magnetic field was a mystery, the first order question being whether it was internally generated or a result of electric currents induced in the surface or in the tenuous atmosphere of Mercury by the solar wind. Another visit to Mercury would be required to resolve the question.

The high-energy charged particle experiment recorded four unusual events during the first encounter. The first of these events was a low

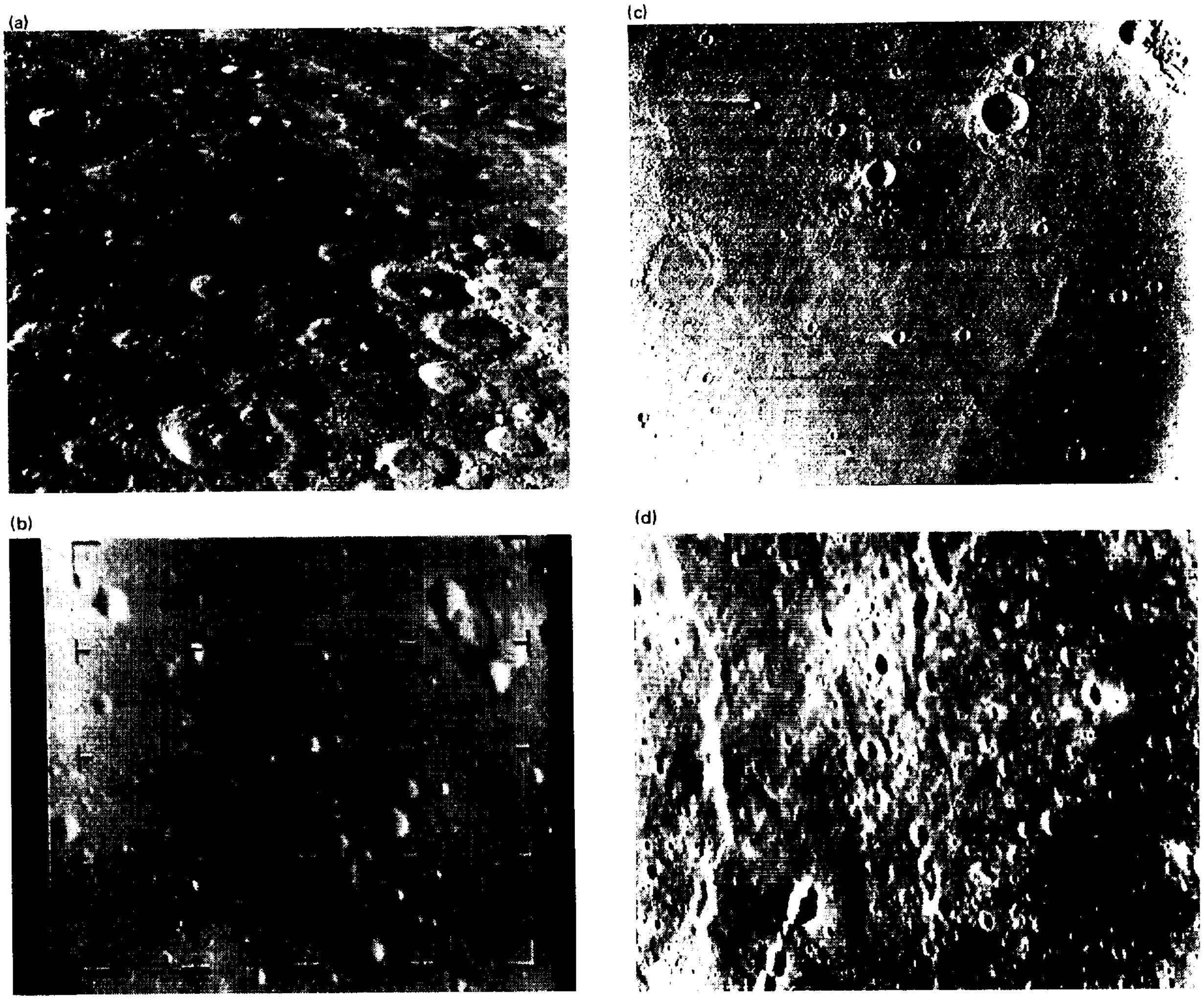


Fig. 7-15. Although superficially the plains of Mercury (a) seem similar to those of the Moon and Mars, closer inspection reveals significant differences. The Moon (b) shows a surface that has been saturated with ejecta and secondary impacts. Mars (c) shows a surface that has been partially smoothed by wind erosion. Mercury's surface (d) may not have been covered as completely with secondary craters and ejecta as has the Moon.

counting rate, which was probably a 600-mi-wide population of residually trapped low-energy electrons. The next two were impulsive events of large fluxes of approximately 300-keV electrons and 550-keV protons. The events are notable because of their fast onset times and the periodic nature of the counting rates. These facts impose severe constraints on the acceleration mechanism. All three events were observed in the magnetosphere. The fourth event was observed in the boundary between the magnetosphere and the bow shock. This event was composed of 300-keV electrons whose counting rate varied with a marked 5-sec periodicity.

Radio tracking of Mariner showed that Mercury is also much closer to being a perfect sphere than is the Earth. The mass of Mercury was measured to 100 times greater accuracy than previously, i.e., to within one ten-thousandth of the mass of the Sun (Fig. 7-16). Mariner determined that Mercury does not possess an ionosphere greater than one hundred-thousandth that of the Earth. Although Mercury is virtually without an atmosphere, the planet does have more helium than the Moon, possibly originating from radioactive decay of uranium and thorium or capture from the solar wind.

A night temperature low of 90 K (−297°F) was measured by Mariner's infrared radiometer just before dawn on Mercury. The maximum daytime temperature in late afternoon was 460 K (369°F). This temperature difference between night and day is enormous. But at times, when Mercury makes its closest approach to the Sun, the range can reach 650 K (1170°F): greater than on any other planet in the Solar System.

The temperature gradient measured between Mercury's light and dark sides offers further proof that its surface is very similar to the Moon: an insulating blanket of dust pulverized by meteoritic impacts. A few outcroppings of rocks and freshly formed craters cause slight temperature variations. But generally the soil is most probably very light and porous, with an appearance and bearing strength similar to lunar soil. An astronaut's footprint on Mercury would be almost indistinguishable from one on the Moon.

Man's first glimpse of Mercury at close hand was quite brief, yet Mariner 10 returned several thousand photographs and tens of thousands of non-imaging measurements of the planet's surface and environment. The planet had been revealed to be an intriguing combination of Earthlike and Moonlike characteristics, a body whose early history, the record of which is preserved on its ancient surface, is an important piece in the puzzle that is the origin of our Solar System. As had been the case with earlier planetary missions, a few hours of spacecraft observations had added more to man's store of knowledge about a little-known planet than centuries of Earth-based observations.

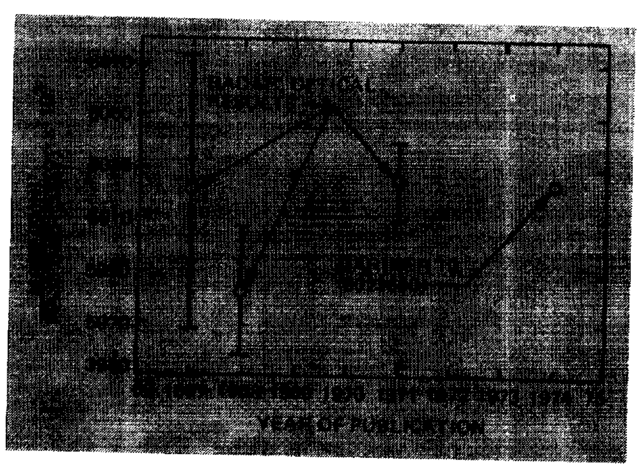


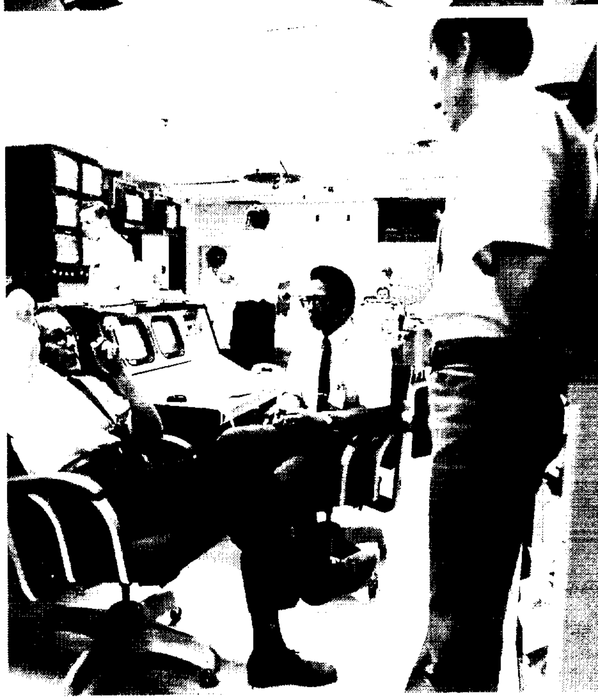
Fig. 7-16. The radio experiment made with Mariner 10 allowed the mass of Mercury to be determined with much greater precision than had the best earlier measurements made by radar and optical observations.





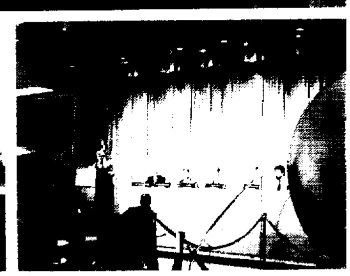


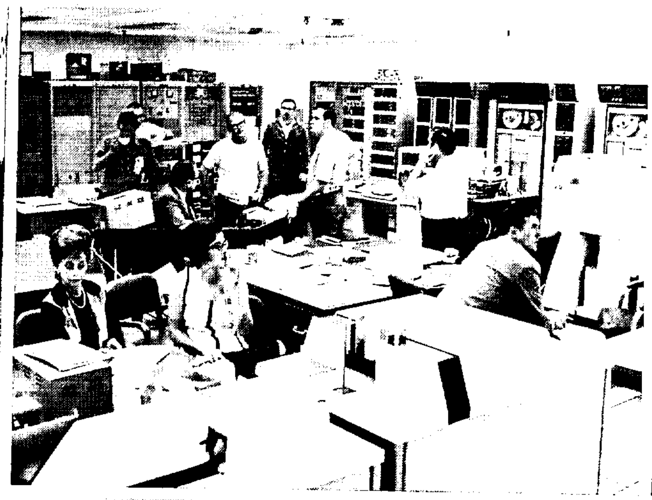












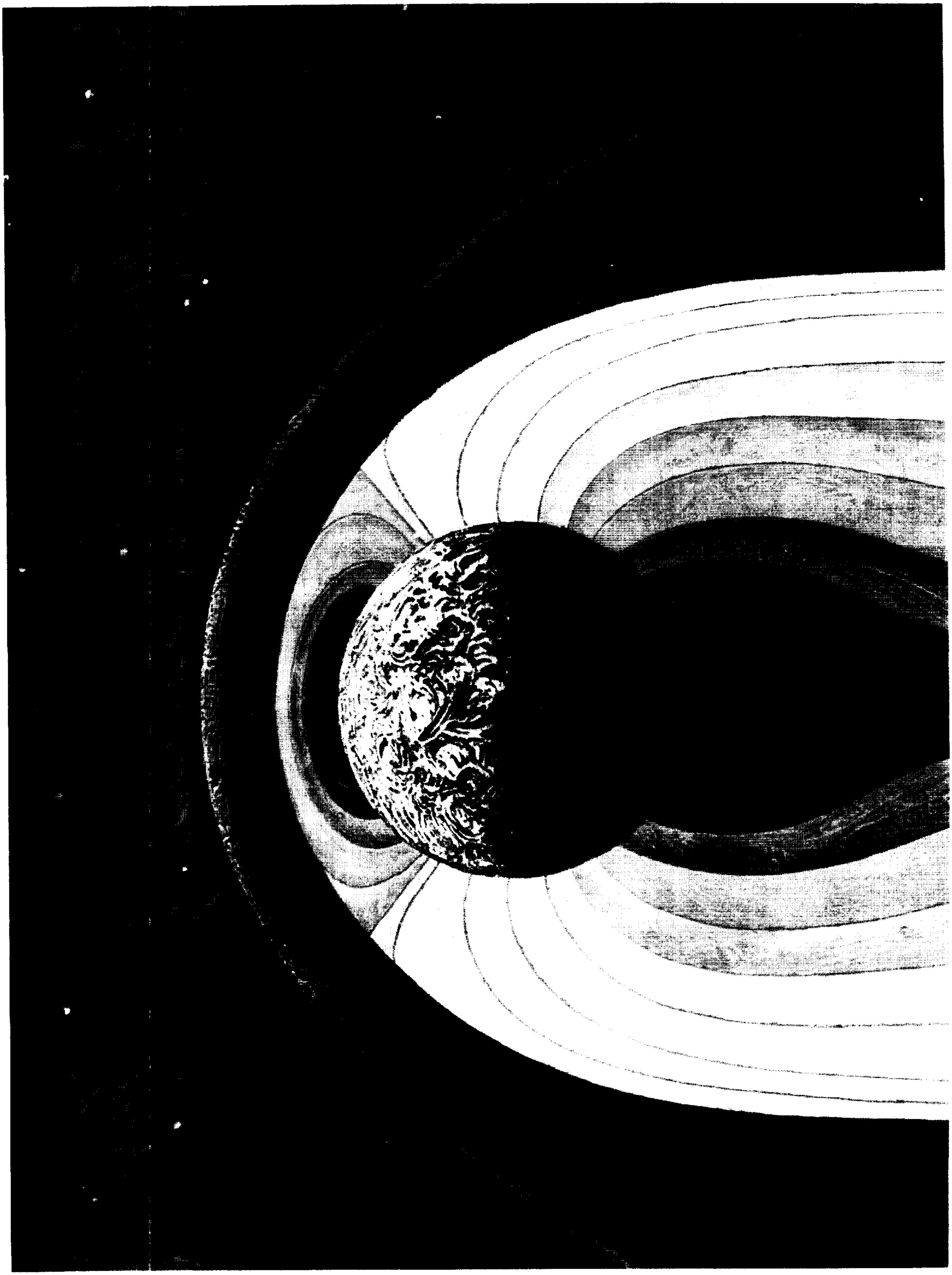










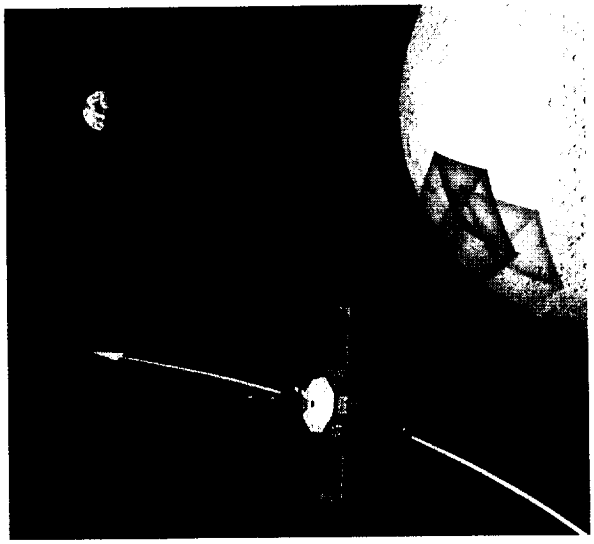


Chapter 8
Return to the Innermost Planet

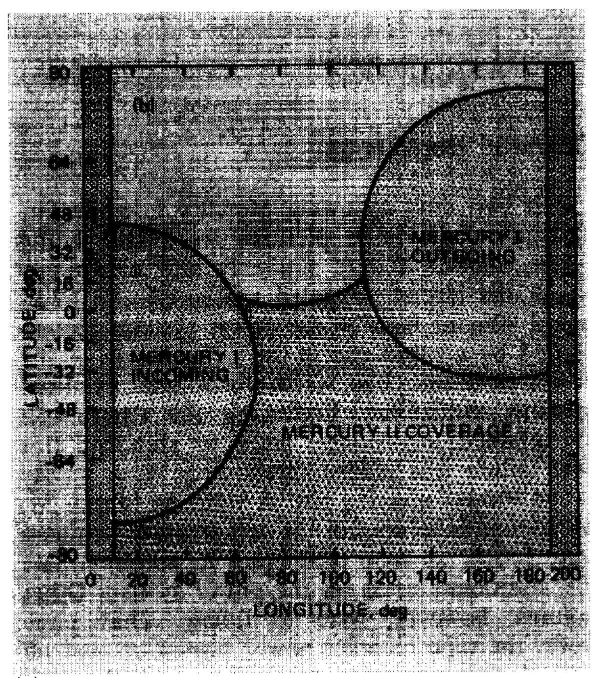
FOLLOWING THE FIRST encounter with Mercury, several more trajectory corrections were needed to direct the spacecraft into an orbit that would permit a return to Mercury on September 21, 1974. With suitable corrections Mariner 10 could again pass by Mercury, this time at 50,000 km (31,000 mi) above the daylight side. The TV optics design is such that the altitude provided substantial expansion of the photography of Mercury at 1 km (5/8 mi) resolution. Exactly the same face of Mercury would be illuminated by the Sun, but the daylight pass would allow photographs to be obtained that would tie together the two halves of Mercury seen at the first pass (Fig. 8-1). Then scientists expected to be able to make a detailed and accurate map of almost one complete hemisphere of this innermost of the planets to a level of detail equal to that on maps of the Moon before the space age. Targeting for the second encounter was chosen such that a third encounter could also be achieved in order that the important question of the nature of Mercury's unexpected magnetic field (i.e., whether it is intrinsic to the planet or induced by the solar wind) could be answered. Figure 8-2 shows the aim points for the three Mercury encounters.

Ominous Beginnings

Just two days following Mercury I, while far-encounter television pictures were still being taken, another failure suddenly and alarmingly struck the already crippled spacecraft. An additional 90-watt load on the power system, accompanied by a rapid rise in the temperature of the power electronics bay, startled exuberant but tired mission controllers. Following the early, still unexplained switchover, main to standby, this new failure was indeed foreboding. At a hastily called Project meeting late at night on March 31, workarounds to control the temperature problem were found, as were techniques to accommodate the additional stress on the power system. Other failures, however, were to follow. That same week, the tape recorder power turned on and off several times without command, and the unit soon failed altogether. Commands to change the transmit power level to the radio system proved ineffectual. The flight data subsystem experienced a failure which eliminated many of the engineeering data channels, thereby increasing the difficulty of nursing the ailing spacecraft twice more around the Sun and to reencounter Mercury. The oscillation problem had robbed Mariner of most of its



(a)



(b)

Fig. 8-1. The second encounter with Mercury allowed Mariner 10 to fly by the planet on the sunlit side, thereby filling in the missing areas between the two sections photographed at the first encounter. This second encounter took place on September 21, 1974. Additionally, in this encounter Mariner was able to obtain good views of the south polar region of Mercury. An artist's concept of the second flyby is shown in (a); (b) shows the added coverage obtained of the illuminated hemisphere.

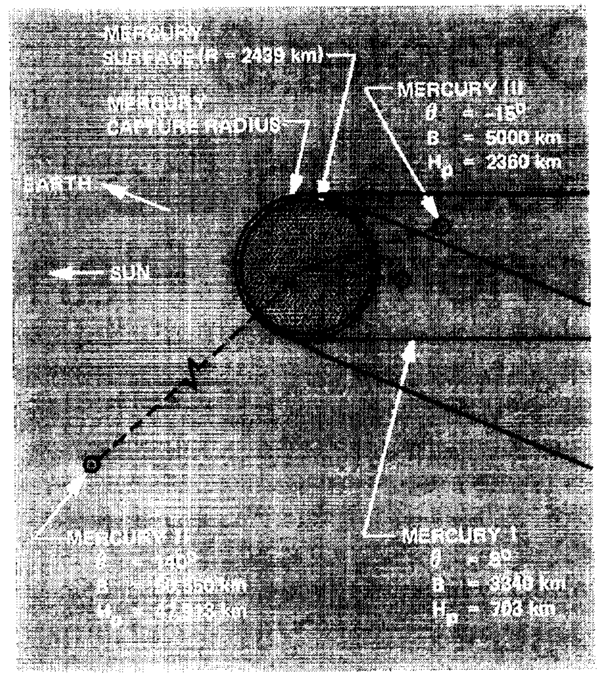


Fig. 8-2. The selection of aim point was important to permit a third encounter with Mercury six months later. The three aim points for the three encounters are shown in this diagram.

attitude control gas, and analysis showed that gas usage would have to be reduced well below the normal cruise rate to last until Mercury III. Further, multiple trajectory correction maneuvers had to be conducted (five were finally required between the first and third encounters), meaning that a way had to be found to use the gyros without causing the oscillation problem. The only technique available to reduce gas usage, which involved using the solar panels and high-gain antenna as solar "sails," was as yet little understood. Only limited experience had been gained so far during the mission with regard to this unplanned method. The prospects of achieving a third encounter therefore seemed dim, and Mercury II, although far more likely, was by no means assured.

A fourth trajectory correction maneuver was commanded for mid-May 1974. Because only one TCM had been used between Venus and Mercury I, this fourth maneuver was large. To prevent overheating of the rocket engine, the maneuver was programmed in two stages. A burn on May 9 produced a velocity change of 50 m/sec (164 ft/

sec), and on May 10 the second firing produced a velocity change of 27.6 m/sec (91 ft/sec). This two-phase maneuver refined the aiming point of the spacecraft to 46,000 km (29,000 mi) above the sunlit hemisphere of Mercury.

Mariner 10 reached solar conjunction on June 6, 1974, when it was on the opposite side of the Sun from the Earth (Fig. 8-3). During this period, communications with the spacecraft were interrupted. The dual-channel S- and X-band signals emitted by the spacecraft had to pass within 1.67 deg of the Sun's surface as viewed from Earth. Effects of the solar corona's electron clouds were recorded at the DSN Goldstone station. The primary effects were to cause the radio signal to scintillate, like a star twinkling in the night sky. A phase delay of the signal also occurred. Analysis of the difference in doppler effects on the S- and X-band signals yielded important information regarding the radial electron density distribution in the outer corona of the Sun.

The influence of the Sun's corona on the range data received at X- and S-band became quite noticeable as conjunction approached. Soon the difference reached 3.6 microsec; a maximum of about 5 microsec was expected at closest approach. Effects of the Sun's enormous gravitational field were expected to reach as high as 160 microsec in an experiment to verify the effects of general relativity on the radio signals.

On July 2, 1974, an important fifth trajectory correction maneuver had to be made. Mariner 10 was not far from the Sun as seen from Earth, being on the far side of the Sun, and when the cold gas jets turned the spacecraft into the position for the maneuver, the telemetry signals being displayed in the Mission Operations Center all dropped to zero. The pens on the plotter made straight lines; communication had been broken. But the stored commands were being executed. The spacecraft was automatically commanded to roll 56.1 deg, then pitched 57.8 deg. The rocket engine fired for 18.8 sec to cause a velocity change of 3.32 m/sec (almost 11 ft/sec). First indication that the spacecraft had performed its maneuver came from the doppler data. A small group looking at the readouts of the doppler residuals showed the results to Gene Giberson and N. William Cunningham (NASA Headquarters Program Manager, who was visiting JPL). The maneuver looked good. Mariner 10 seemed all set for its second rendezvous with the inner planet. A short while later the spacecraft commanded itself back to the cruise orientation and telemetered data were again received.

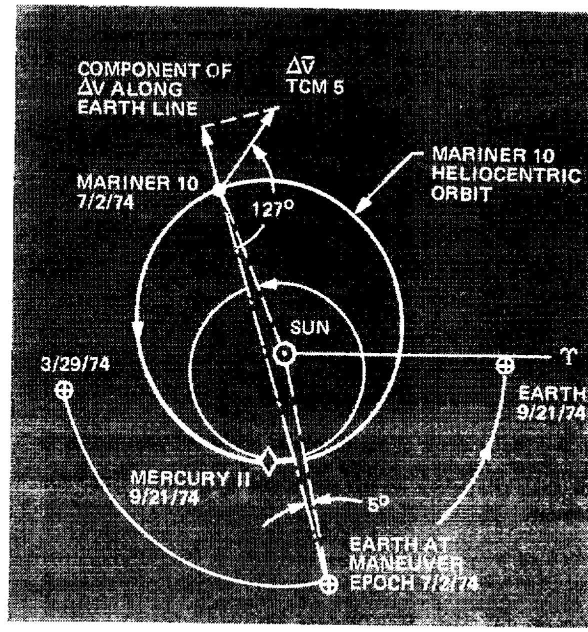


Fig. 8-3. On its long journey around the Sun to the second encounter, Mariner passed on the far side of the Sun from Earth through superior conjunction. Contact with Earth was lost for a short while. A fifth trajectory correction maneuver had to be made soon after solar conjunction with the spacecraft at almost its most distant point from the Earth, as shown in this diagram.

Without the fifth correction, Mariner 10 would have passed about 34,000 km (21,000 mi) from Mercury's sunlit side, at a point about 45 deg south of the planet's equator. With its new orbit velocity, Mariner was expected to pass 16,000 km (10,000 mi) farther away from Mercury, or about 50,000 km (31,000 mi) at about 40 deg south latitude (see Fig. 8-4). There were two reasons why this fifth correction maneuver was commanded. First, a more favorable passage was desired at the second Mercury encounter (which became known as Mercury II) in terms of science data return. The second objective was to allow retargeting of the resultant trajectory between Mercury II and a possible Mercury III to a variety of realizable aiming points at Mercury III which would not exceed Mariner 10's remaining trajectory correction capability.

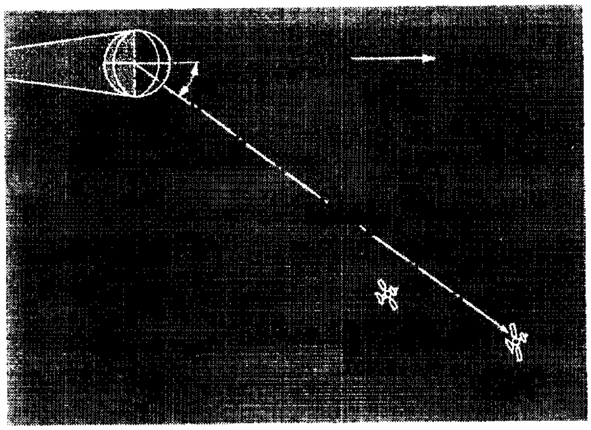


Fig. 8-4. As a result of the trajectory correction, aim points for the second encounter, termed Mercury II, brought the spacecraft farther out on the sunlit side to gain improved TV coverage.

Focus on the Southern Hemisphere

Point of closest approach during the second encounter occurred at 1:59 p.m. PDT on September 21, 1974, and some 500 pictures of Mercury were returned during the three-day encounter sequence. This second encounter provided a substantial increase in area of the planet covered by detailed mosaics (Fig. 8-5), in extending the coverage from 50 to 75% of the illuminated hemisphere, and it showed details in the south polar region (Fig. 8-6). No totally new terrain types were found, increasing scientists' confidence that Mercury I conclusions were based on a representative sample of the Hermian surface. Scarps similar to those noted at the first encounter were found in southern latitudes, thereby verifying the global character of the forces which formed them.

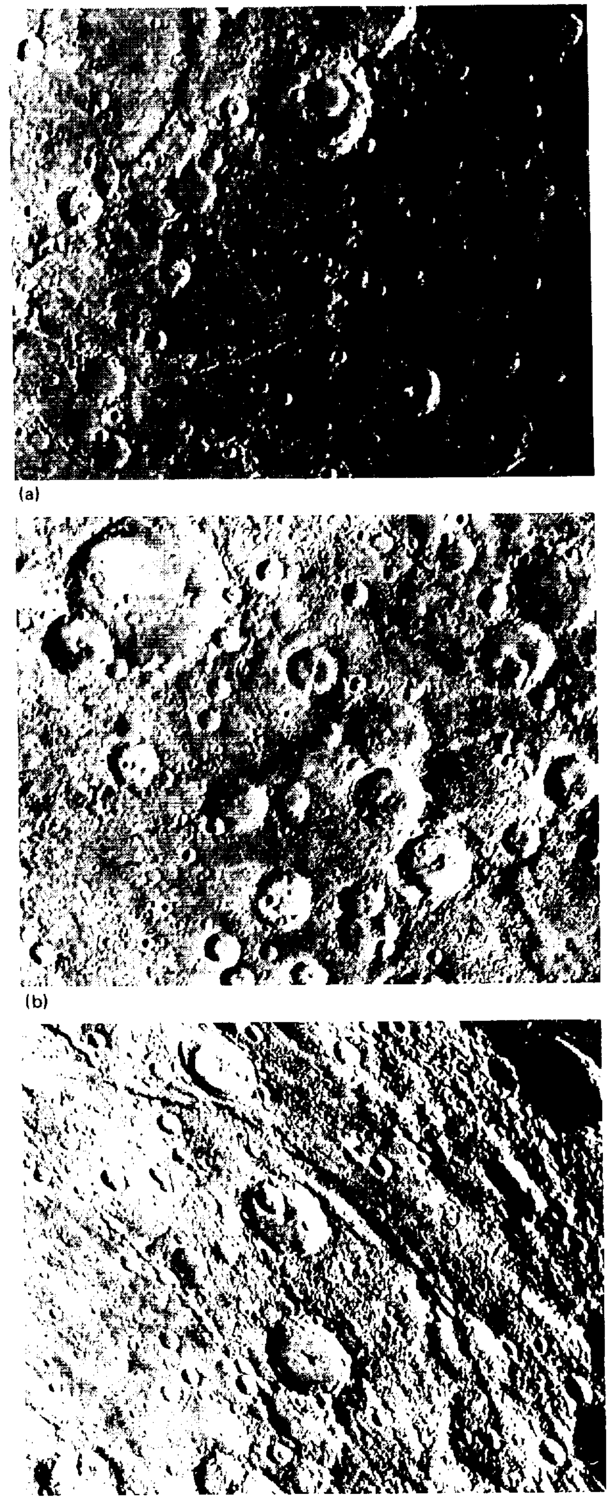


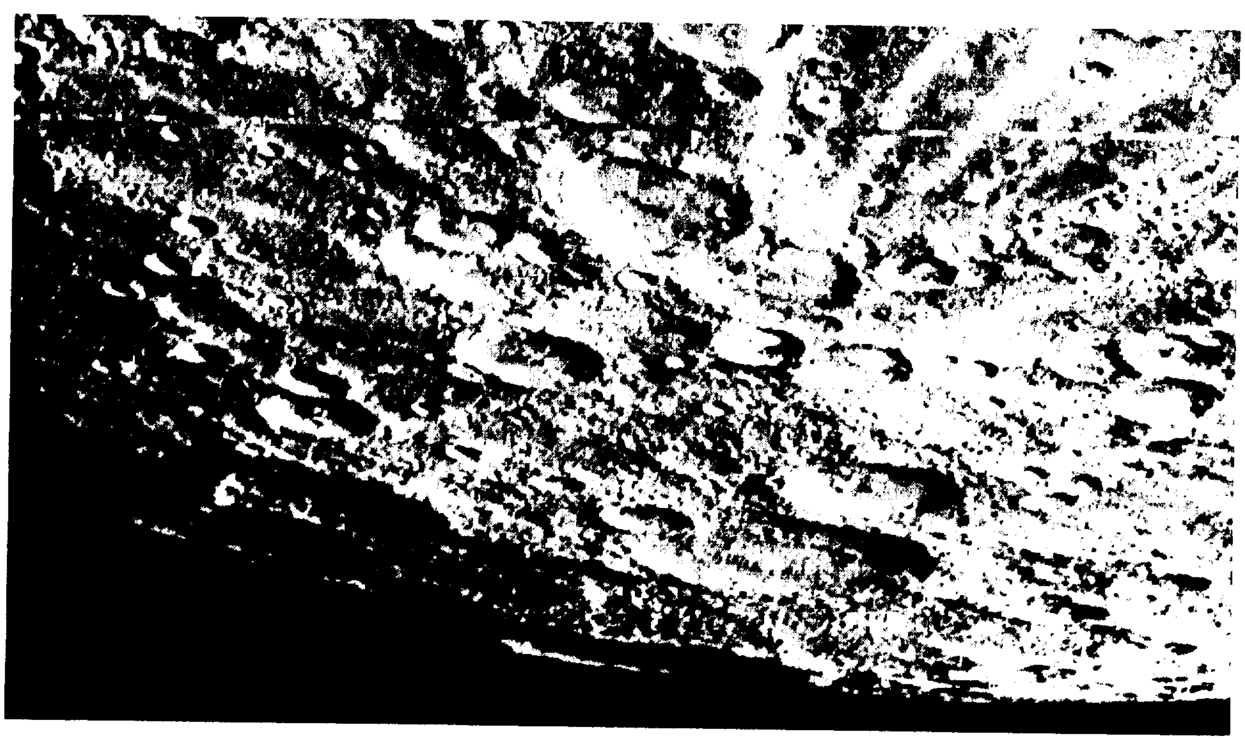
Fig. 8-5. The new pictures were fantastic. A southern hemisphere area of heavily cratered terrain (460 by 650 km, 285 by 400 mi) on which a prominent scarp extends several hundreds of kilometers at the upper left is shown in (a). The smallest details measure about 1.7 km (1 mi). Another densely cratered region containing a scarp which rises about two km (7500 ft) above the surrounding area is shown in (b). The scarp shown in (c) is more than 300 km (185 mi) long. These structures are explained as compressive faults caused when the core of Mercury shrank after most of the craters had been formed on the surface.

Mercury II was an epic encounter, the first time any spacecraft had returned to its target planet for a second look. The second encounter was made when the spacecraft was much more distant from Earth than at the first encounter, and in order to get the full complement of TV images back to make a complete mosaic of the planet, engineers at the Goldstone station had to develop an unusual antenna configuration. They connected the three big Goldstone antennas together—one 64-m and two 26-m antennas—with microwave links and operated them as one large antenna. The error rate for this distant encounter was thereby reduced to about 3 bits per hundred, and pictures of superb quality were obtained in real-time.

These pictures provided mosiacs over large areas of the planet's surface, with coverage of some areas from several different viewing angles. Many of these mosaics are reproduced in an appendix. The additional coverage of the planet by the second encounter is shown on the U.S. Geological Survey map reproduced in Fig. 8-7 and one of the mosaics in Fig. 8-8.

The second flyby was mainly devoted to imaging science, since the spacecraft was too far from the planet to obtain significant data with some of the other science experiments. However, the ultraviolet experiment was able to make good use of the distant sunlit-side encounter. The slit of the spectrograph was commanded through many slow drift scans across the surface of the planet. Thus, good ultraviolet data were obtained to set even more accurate upper limits of the density of the helium atmosphere of Mercury than those set at the first encounter, i.e., less than 10^{-15} the density of Earth's atmosphere. Also during this encounter, the emission lines of helium were seen again.

Fig. 8-6. On this second flyby, Mariner 10 was able to obtain close-ups of the south pole of Mercury, showing that no different land forms exist in the polar region. Also, the photographs show that the compressional scarps extend into the polar regions. The pole is located inside the large crater, 180 km (110 mi) in diameter, on Mercury's limb (lower center). Just above and to the right of the south pole is a double ring basin about 200 km (125 mi) in diameter. A bright ray system, splashed from a 50-km (30-mi) crater, appears at the upper right. The picture was taken at a distance of 85,800 km (53,200 mi), within two hours of Mariner's approaching closest to Mercury.



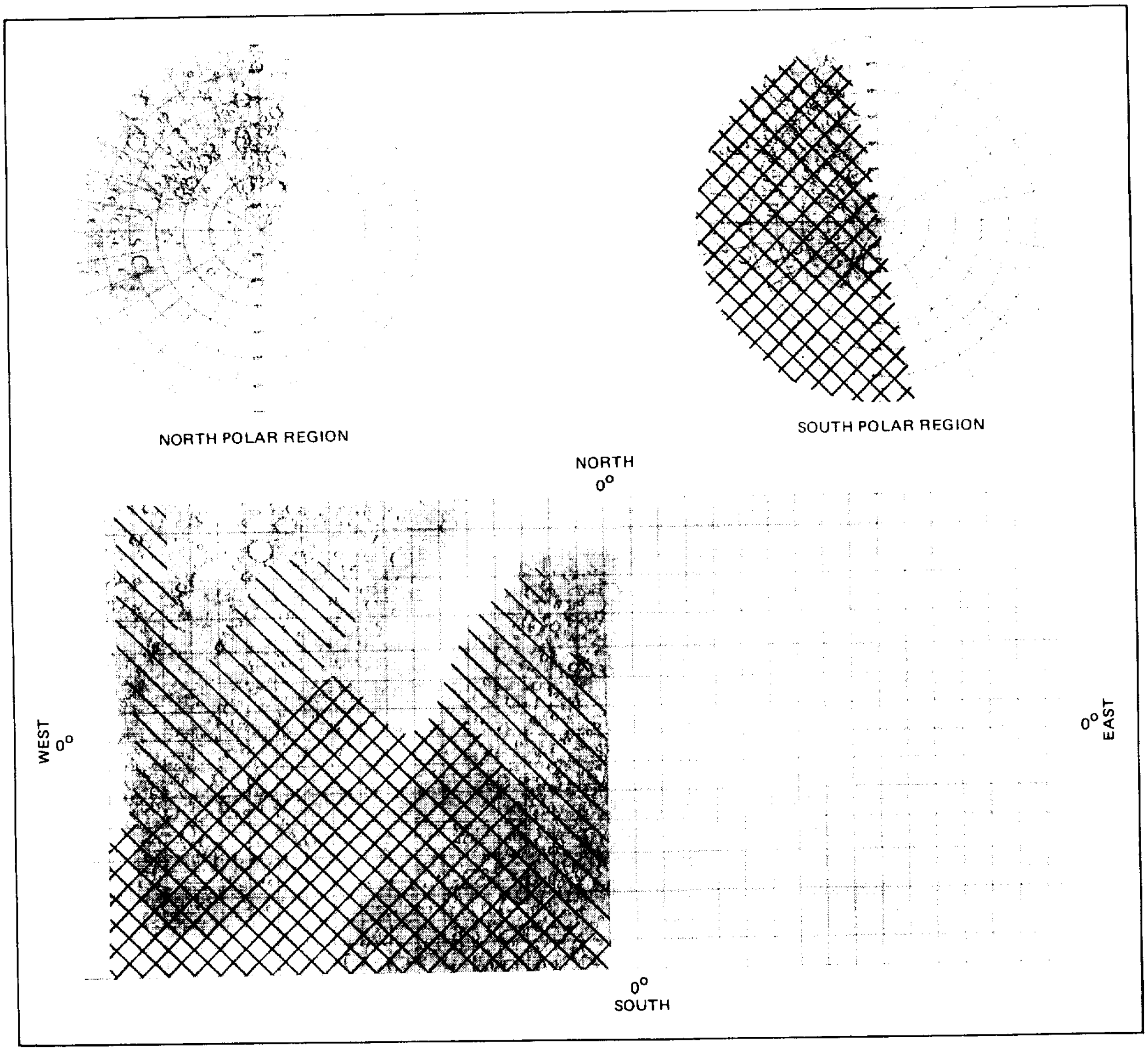


Fig. 8-7. The additional coverage of Mercury by the second encounter is shown by the hatched portion over this USGS map made on the basis of the first encounter.

In this second encounter a navigational technique was tested that would be essential for subsequent missions to the outer planets. All interplanetary flights to date relied solely on Earth-based radio measurements for navigation. Project scientists decided to conduct experiments with Mariner 10 to find out if optical navigation is practical. From September 17 through 19, some one hundred pictures were taken by the TV imaging system to obtain angular measurements between Mercury and stars. First results showed that the experiment was successful, demonstrating that long missions to outer planets will be able to use this technique to navigate spacecraft through the intertwining orbits of satellites of the big planets, Jupiter and Saturn.

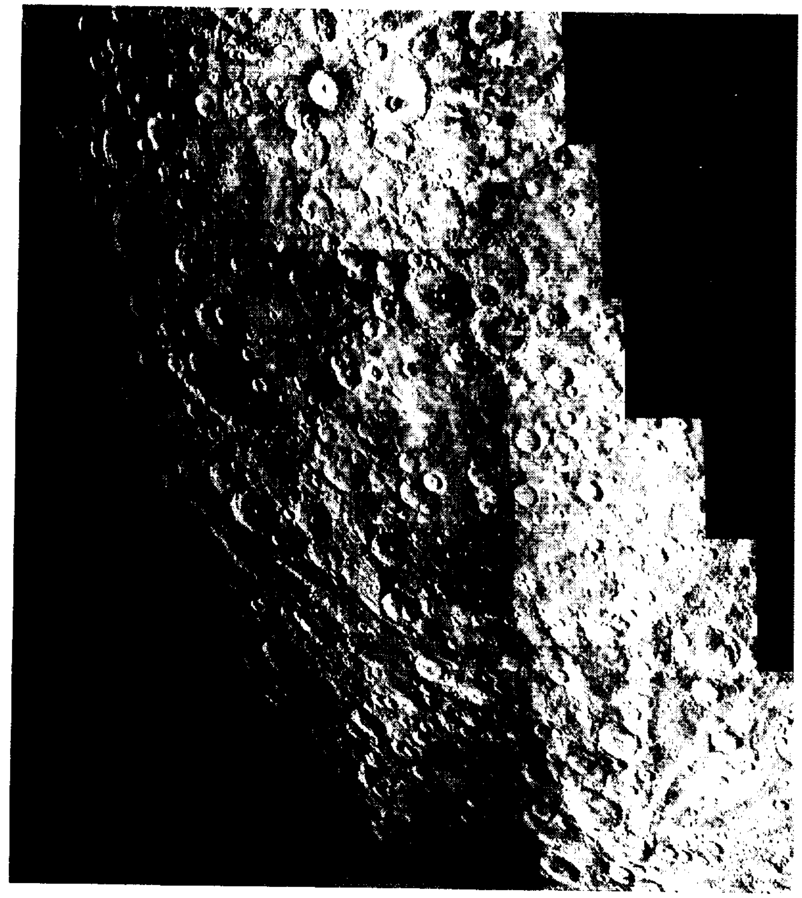


Fig. 8-8. The new mosaics produced from the pictures returned from Mercury II were equally as good as the two from the first encounter. Mercury II mosaics gave many different panoramas of the same area seen at various viewing angles. These mosaics are reproduced in Appendix A. The one shown here covers the heavily cratered south polar region as seen from a distance of about 65,000 km (40,000 mi). The south pole is just off the field of view at the bottom, and north is at the top. Numerous scarps are revealed, some of which are several hundred kilometers long and transect and distort large craters. Ray systems associated with two fresh craters are prominent at the top and bottom of the picture. Small areas of relatively smooth, flat terrain are visible near the center of the field of view and appear to fill a large, badly degraded, circular basin 350 km (220 mi) in diameter near the terminator.

Attempting a Third Visit

After Mercury II, Mariner 10 was placed back in the cruise mode in which the high-gain antenna and solar panels were used as light-pressure torquers to save attitude control gas for a third encounter. The antenna was placed in a position whereby solar radiation pressure could be used to maintain the spacecraft's correct orientation, and the solar panels were differentially tilted to minimize roll jet gas usage. These techniques sharply reduced the expenditure of the spacecraft's precious nitrogen supply, but more extreme measures became necessary.

On October 6, the Canopus star tracker, distracted by a bright particle passing through its field of view, lost lock on the reference star, and the spacecraft went into an uncontrolled roll. The automatic reacquisition sequence had been inhibited, and repeated reacquisition attempts using commands timed on the basis of the star tracker roll error signal telemetry were unsuccessful. Each of these attempts required the momentary turn-on of the gyros, and the resultant oscillation events depleted the gas supply below that required to achieve Mercury III (160 days of cruise remained). Roll axis stabilization had therefore to be abandoned, and a "roll drift" mode adopted, whereby the spacecraft was allowed to roll slowly, the rate being controlled by differentially tilting the solar panels. The roll rates had to be maintained quite low to prevent excessive use of the pitch and yaw jets, and also to allow gyro turn-on for trajectory correction maneuvers and pre-encounter reacquisition without inducing an oscillation. The method was made more difficult by the loss of engineering telemetry channels mentioned earlier. The Canopus intensity channel, from which a "star map" capable of defining roll position quite accurately could be calculated, had been lost. The "roll error" signal from the tracker remained, but this gave only an approximate position of those stars bright enough to be acquirable by the tracker. Since at no time during the Mercury II–III transit were there more than three such stars, roll position knowledge was difficult to obtain with any precision.

One technique to obtain this information which proved very useful was measurement of the intensity of the signal from the low-gain antenna, which varied with roll position because of the nonuniformity in the antenna's radiation pattern (measured before launch) and its noncentral position on the spacecraft. This measurement was, in fact, the sole indication of roll position and rate upon which the critical command to stop the spacecraft for reacquisition was sent just hours before the third encounter. But "roll drift" worked, reducing gas consumption to some 25% of normal cruise usage, allowing Mariner to reach Mercury III with a slim margin (the gas supply was exhausted just a few days following encounter).

The continuous rolling of the spacecraft complicated the navigation task, in that it introduced a modulation on the doppler measurements because of the off-center position of the low-gain antenna. This complication required special modifications to the complex orbit determination computer programs. The problem was further aggravated by sharply reduced station coverage (Mariner could be tracked less than 20% of the time because of the needs of the Pioneer and Helios programs). Nevertheless, three trajectory correction maneuvers were successfully completed during this period, putting the spacecraft on a trajectory which produced the closest planetary flyby yet accomplished (Fig. 8-9).

A few days before the encounter, trouble again hit the spacecraft and added considerable drama to the final stages of this extended mission. During the attempt to reacquire the reference star Canopus, the spacecraft rolled into a null position on the low-gain antenna, and communications with Earth were broken. To compound the problem, the spacecraft could not be commanded by the smaller DSN antennas, and there were demands on the bigger antennas to communicate with other spacecraft: Pioneer 11, on its way to Saturn, and Helios, approaching its perihelion passage. To save Mariner, the German controllers of Helios were asked to surrender some of their scheduled receiving time on the big antennas. Even though this was the period of maximum scientific interest during the Helios mission, they acceded to the Mariner project's request. As a direct result, commands reached Mariner from the big antenna at Madrid, and the spacecraft broke from its null mode and achieved its correct orientation for the third flyby of the innermost planet. It had been a close call–reacquisition had been achieved just a few hours before closest approach.

Although this flyby was aimed primarily at obtaining data on the magnetic field of Mercury,

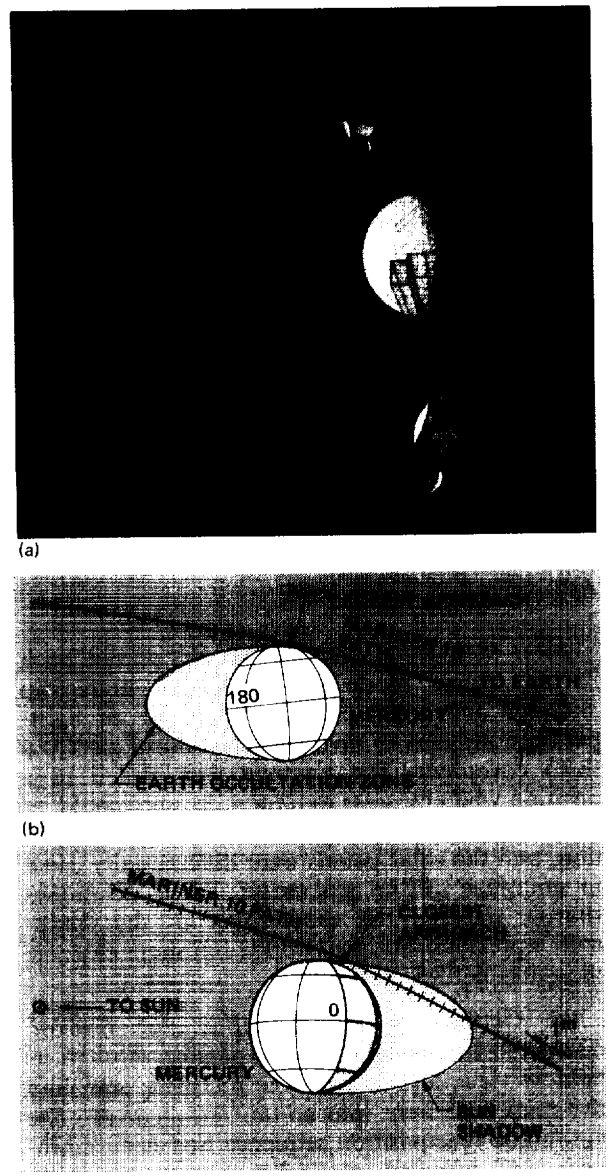
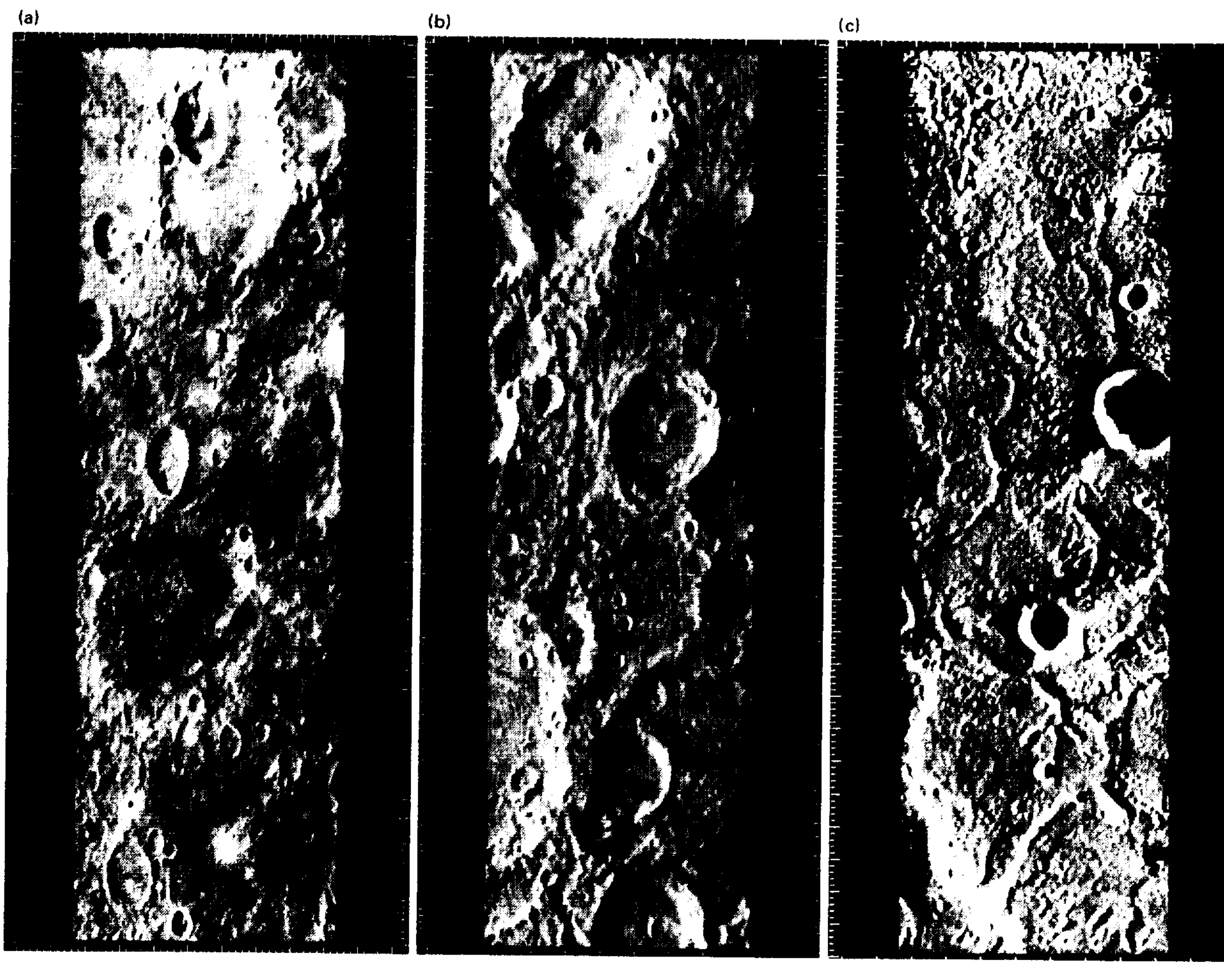


Fig. 8-9. The third encounter is graphically shown in this artist's concept (a), while (b) and (c) show the flight path as seen from the Earth and from the Sun.

the incoming and outgoing paths provided opportunities for imaging science as they did at the first encounter. The cameras were directed to produce high-resolution mosaics of areas of interest discovered at Mercury I. The third encounter produced some remarkably detailed pictures of small areas of the Hermian surface on which objects as small as 137 m (450 ft) can be identified. Figure 8-10 provides a selection of these pictures.

As anticipated, the important science results from the third encounter were those obtained by the particles and fields observations. The magnetic field experiment produced evidence that the field of Mercury is intrinsic to the planet and not induced by the action of the solar wind. Norman Ness, principal investigator for this experiment, calculated the time of events expected to be observed by Mariner 10 at Mercury III, assuming that the planet's magnetic field is a scaled-down

Fig. 8-10. High-resolution pictures, each only a quarter frame, were obtained at the third encounter, Mercury III. In the upper portion of (a), which was taken from a distance of 67,000 km (41,500 mi) on March 16, 1975, a multiple impact feature of three craters of different sizes nested within the largest is shown. The smallest crater is about 15 km (9 mi) in diameter. The bright feature at the bottom was caused by impact of a meteorite; it is a fresh crater. Craters ranging in size from 30 to 50 km (18.5 to 31 mi) are shown in (b). It was taken at a distance of 65,000 km (40,000 mi), one hour and 45 min before closest approach. The fractured and ridged plains of the floor of the Caloris basin are shown in (c). The area is located at 31°N latitude and 183°W longitude. The picture was taken at a range of 19,000 km (11,800 mi), 34 min after the spacecraft swept past Mercury for the third and final encounter.



version of the Earth's field. The actual times of passage through the bow shock, the magnetopause, and the maximum field were almost exactly as predicted (see table).

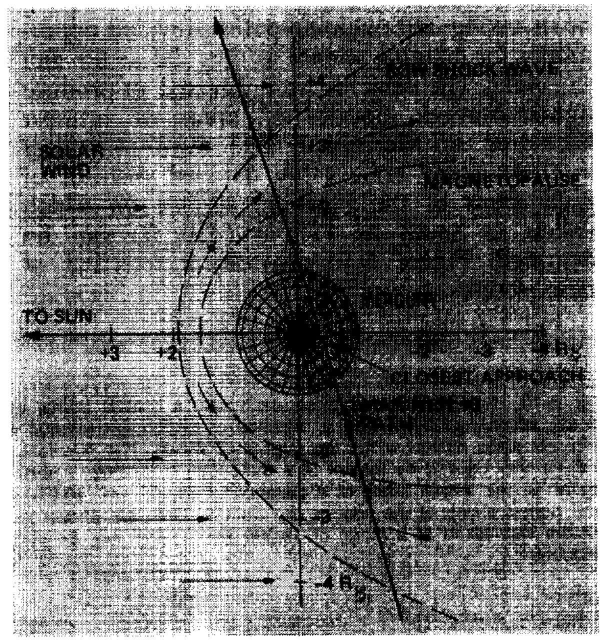
Magnetometer Results

	Time of observation (PDT), hr:min	
Significant Events	Predicted	Actual
Bow shock	3:31 ±02	3:31
Magnetopause	3:39 ±01	3:39
Maximum field*	3:49 ±01	3:49
Magnetopause	3:54 ±01	3:56
Bow shock	3:58 ±02	3:59

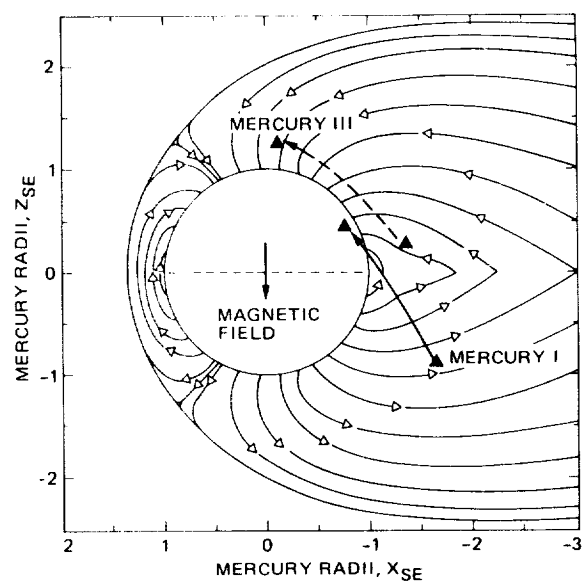
*Amplitude predicted was 200 to 500 gamma; actual was 400 gamma.

In addition, observations of the low-energy solar wind electrons revealed that the magnetosphere of Mercury fits very closely to a scaled-down Earth's magnetosphere (Fig. 8-11), thereby reinforcing the results of the magnetometer experiment. Finally, the observations of relativistic particles confirmed that Mercury, like the Earth, has a magnetically neutral "tail," with a dividing neutral sheet. From this region, explosively accelerated bursts of electrons and protons are ejected. These brief, high-intensity bursts, first detected on Mercury I, are believed to originate from cancellation of magnetic fields.

Mariner left Mercury behind and started another orbit of the Sun, its maneuvering gas just about exhausted. The end came on March 24, 1975, when the final depletion of the nitrogen supply was signalled by the onset of an unprogrammed pitch turn. Commands were immediately sent to the spacecraft to turn off its transmitter, and radio signals to Earth ceased. A silent Mariner 10, its extended mission completed



(a)



(b)

Fig. 8-11. Mariner 10's path through the third encounter passed over the planet. Looking down from the north, (a) shows the interaction of the solar wind with the magnetic field of the planet. The crossings of the bow shock wave and the magnetopause corresponded with the times predicted from the measurements made during the first encounter, thereby confirming that the magnetic field of Mercury is intrinsic to the planet. An equatorial plane view of the planet's magnetic field lines is given in (b), which shows portions of the path of Mariner 10 through the field at the first and third encounters.

despite the many obstacles, continued its lonely orbiting of the Sun. A few days later, the U.S. Postal Service issued a commemorative stamp (Fig. 8-12) honoring the project in ceremonies at the Jet Propulsion Laboratory.

Mariner 10's observations of the two inner planets, with three observations in one mission of the innermost, added another to the long series of NASA firsts in the golden age of planetary exploration.

In March 1940 the planets Mars, Saturn, Venus, Jupiter and Mercury were all lined up in that order in the evening sky, a brilliant celestial necklace of other worlds. There were few people at that time in science or engineering who would have thought that mankind would explore all these planets with spacecraft within 40 years. Yet now that Mariner 10 has visited Mercury, Pioneer 10 has visited Jupiter, and Pioneer 11 has safely passed Jupiter and is on its way to Saturn for a flyby in 1979, this tremendous feat of interplanetary exploration has been accomplished, and man has become more aware of the Solar System and the place in it of the Earth.

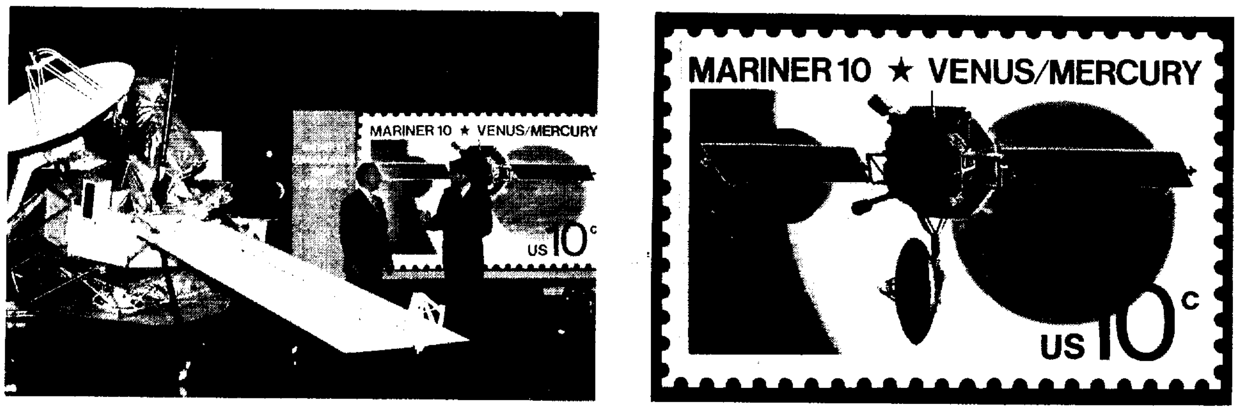
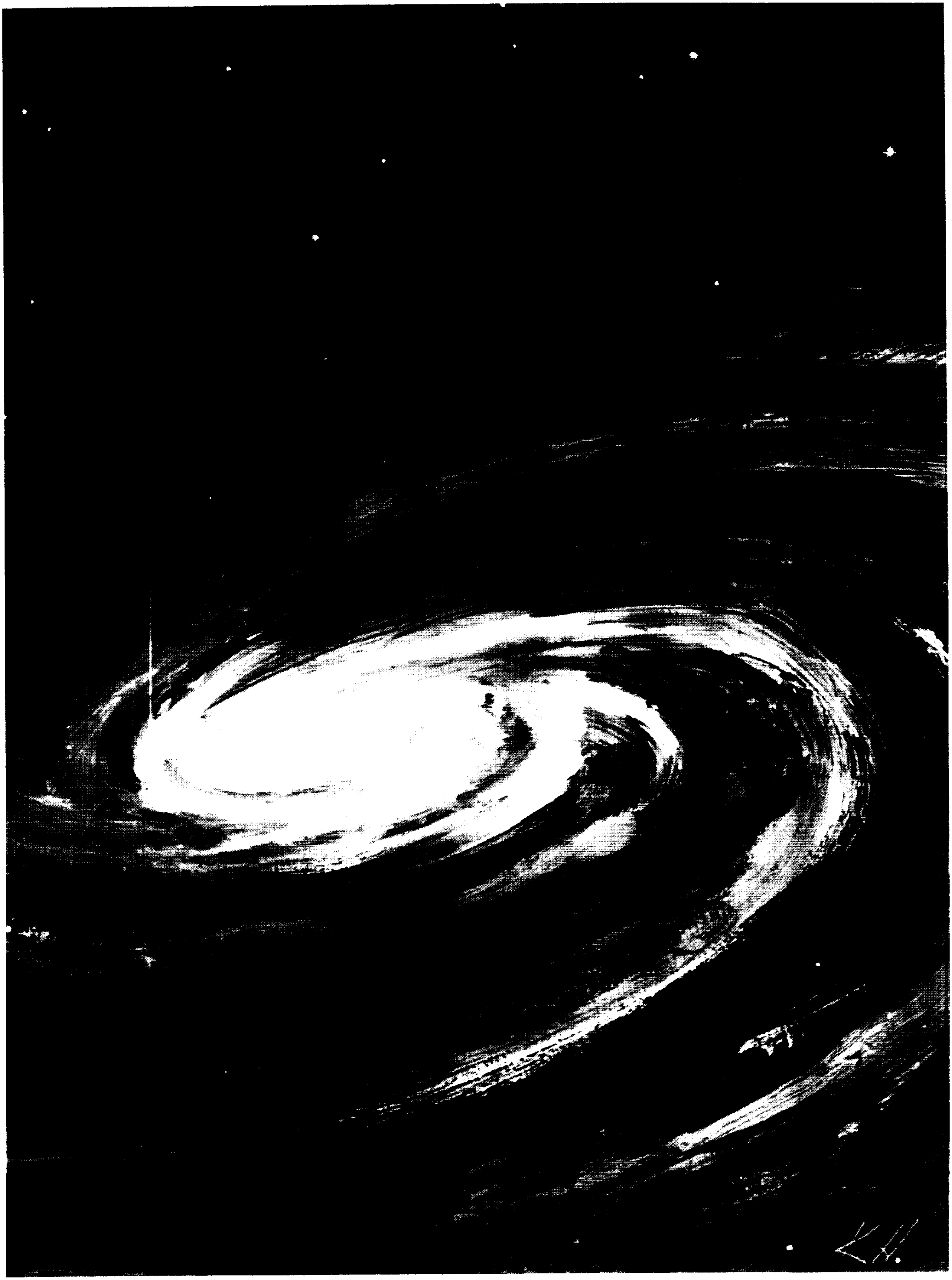


Fig. 8-12. Commemorative stamp issued by the postal service honoring the achievements of Mariner 10.



Chapter 9
A Clearer Perspective

MARINER 10 PROVIDED an important addition to man's view of the inner solar system. Previously, the Apollo program had provided a direct sampling of rocks from another world, thus allowing age-dating of planetary material even further back than was possible on Earth because of major disturbances to the Earth's surface following its formation. An orbiting Mariner spacecraft had surveyed the whole of the planet Mars and revealed unexpected surface features, a planet that was partly primordial and partly molded by volcanism and atmospheric effects.

Venus had been visited by a number of American and Soviet spacecraft, and the general nature of its atmosphere and surface conditions determined, with reasonable, but yet untested inferences regarding its internal structure and evolutionary history. Direct observational data on Mercury were sparse. Its mass and density were known, and evidence existed that its atmosphere was at best tenuous. There were no data on Mercury's surface topography or body characteristics, from which both evolutionary history and internal composition might be inferred.

Mariner 10's investigation of Venus yielded a modest, but important increase in knowledge. Fine-scale markings in the upper atmosphere of Venus that are visible only in ultraviolet light were observed. These "cloud" patterns exhibit a rapid rotation with a 4-day period, much faster than that of the planet itself. While the mechanisms responsible for these remarkable features are not yet understood, their eventual elucidation will be of profound importance to our understanding of Venus's atmosphere. Further, observations of the interaction of the planet's atmosphere with the solar wind were extended significantly. These new data, combined with Mariner's direct, highly precise measurements of hydrogen, helium, carbon and argon abundances, provided better insight into the processes by which planetary atmospheres evolve and are modified by the Sun.

But Mariner 10's principal contribution to the study of the Solar System lay, as expected, in the Mercury observations. A major discovery was Mercury's magnetic field. This result was completely unexpected and very exciting. Mercury was known to be a slowly rotating planet, and the early Mariner 10 pictures had shown it to be one which, like the Moon, had not experienced significant crustal modification by internal activity since its infancy. Our best theories told us that planetary magnetic fields were generated by a dynamo effect which was caused by the presence of a molten electrically conducting core within a rotating planet. Another possible explanation would be the induction of a magnetic field by the interaction of a cold, but conductive planet with the fluctuating magnetic field of the solar wind.

This effect could produce a magnetic field similar to one which was internally generated and very difficult to distinguish from the latter in a single observation.

Mercury III provided a second observation. The third encounter results showed unequivocally that the field is of internal origin, and the explanation of Mercury's magnetic field became a sort of scientific "Catch-22." The field had to be either actively generated at the present or a relic of a previous field. With regard to the latter, the "catch" is that the high temperatures which are required for the generation of a field (i.e., temperatures above the Curie point, when metals lose their induced magnetism) destroy induced magnetism once the dynamic field-generating process stops. The "catch" in the presently active (dynamo) explanation is the fact that Mercury's surface shows no evidence of internally generated deformation or volcanism for at least 3 billion years. Thus the best explanation for the origin of the field—i.e., a large, hot, thermally convecting core—seems at odds with the clearly primitive state of the planet's crustal development.

The photographic record of Mercury's surface produced by Mariner 10 has allowed planetologists to take a deeper look at the inner Solar System. Some now see a pattern emerging in which there were five major epochs in the building of the terrestrial planets.

The first epoch was one of major accretion, in which the basic mass of each planet came together from Solar System material in a relatively short time of several million years about 4.5 billion years ago. Whether or not this was an accumulation of particles of the same general composition irrespective of distance from the Sun, or a differentiated accumulation of particles depending upon distance from the Sun, is not yet known.

In the former case, all the inner planets would have started out with basically the same materials, ranging from heavy elements such as iron to lighter volatiles such as hydrogen and helium. Then subsequent evolution of the planets would have caused a change to their present states in which the planets differ radically in composition, some having more heavy elements and fewer volatiles than others.

In the latter, generally more favored case, planets closer to the Sun accreted from material richer in the heavier elements, while the material forming those further from the Sun has a greater proportion of the lighter elements. A chemical gradient model allows the condensation from the primordial nebula of different combinations of chemical compounds at various distances from the Sun; some planets would receive water, others would not. Thus the innermost planets, Mercury and Venus, might have accreted in a zone around the Sun where there was little water, whereas the Earth formed in a zone with an abundance of water.

It is further speculated that following the accretion of the planets there was a period of internal heating during which the original accretionary surface was molded. This appears to some scientists to be borne out by observations of the surface of Mercury from Mariner 10. Between the craters there appear to be many areas of an ancient smoothed surface. Some planetologists feel that an early process of melting is evidenced by these "intercrater" plains and that they are the record of the chemical differentiation which appears to be required to explain Mercury's magnetic field, i.e., heavy materials in the core and lighter elements near the surface. However, this differentiation could have taken place during the actual process of accretion; i.e., the heavy materials might have accreted into a protoplanet which later collected lighter materials as these condensed from the primordial nebula. The question of the timing of Hermian differentiation is now being attacked by scientists specializing in planetary thermal evolution models. Their observational limits have been set by Mariner 10 and lunar age dating.

Between 4 and 3.3 billion years ago, according to the evidence of the lunar rocks, the Moon was subjected to bombardment by swarms of large bodies, which created large impact basins and smaller craters accompanied by secondary and tertiary craters. Then, as abruptly as it commenced, this tremendous bombardment ended.

Comparative studies of the cratered terrains of Mars, and now Mercury, show that these planets, too, were subjected to similar bombardment. Crater densities observed on these three widely separated planets suggest that the source of the bombarding objects could be remote from the inner Solar System, and not necessarily in the asteroid belt, as was thought before the beginning of spacecraft planetary exploration. In addition, the use of a remote source area for this uniform bombardment flux implies simultaneity of the bombardment for all bodies in the inner Solar System. This episodic, nonuniformitarian theory, although philosophically objectionable in terms of the orderly operation of a natural system which can be described statistically, has considerable appeal to those concerned with the practical problems involved in describing the early history of the Solar System. Final heavy bombardment, if episodic, simultaneous and ubiquitous in the inner Solar System, provides a "marker horizon" for dating epochs in planetary evolution. One suggestion for the origin of the bombarding bodies is the penetration of a large (10^{23} grams) body into the inner Solar System on a Venus satellite escape trajectory, followed by its fragmentation as it passed Venus inside the Roche limit (a distance within which the gravitational energy of the larger body causes the smaller one to fragment). Another is a sudden disruption of a very large body in the vicinity of the asteroid belt. Note that the latter model, while not requiring a remote source, still implies simultaneity.

On Mars and Mercury the bombardment did not destroy all the old surface. On the Moon it did. We cannot be sure what happened on Venus, although radar observations do show evidence of large craters on that planet. On the Earth there is steadily emerging evidence of a period of extensive bombardment of the most ancient continental cores like the Canadian shield. In the main, of course, Earth's bombardment history has been erased by subsequent events. However, it is important to note that all the planets of the inner Solar System were most likely subjected to bombardment by asteroid-sized bodies at some time subsequent to accretion and chemical differentiation.

As the impacts subsided, the Moon entered another phase of evolution—volcanism. Lava flowed into the big impact basins and filled the floors of large craters. On the Moon these flows are very evident. Not so on the Earth and Mars. The smooth post-bombardment plains of Mercury strongly resemble the lunar maria, and many planetologists argue that they also represent an epoch of extensive volcanism. Others, however, point out that no primary volcanic features (domes, vents, pit-craters, etc.) have been recognized on Mercury, and caution that the marelike plains may have been formed by impact-melt processes. It has been determined by direct measurement that on the Moon the latest lava flows occurred about 3.3 billion years ago. It appears, based on crater counts, that the smooth plains on Mercury occurred about the same time, assuming a simultaneity in the heavy bombardment of both planets.

The final phase of planetary evolution is represented on the Earth by a tectonic phase in which convection within the mantle gave rise to shield volcanoes, subduction zones, sea-floor spreading centers, and the motion of crustal plates. The major volcanoes on Mars and the great plateau on which they are found represent the manifestation of tectonic processes. On Venus, too, some of the radar data suggest that although Mariner 10 shows an almost spherical planet, much closer to a sphere than is the Earth, the surface itself has great irregularities. This may indicate that convective forces have been actively molding the surface of Venus too.

There have been postulations that Mars may be entering an active phase of tectonism, leading to an Earthlike planet in the future. There has been speculation that the great Coprates chasm represents the beginning of rifts in the continental mass and shows the start of a breakup into continental plates. However, the results of the Mercury encounter, taken in conjunction with comparative crater counts, seem to strengthen the view that the Martian volcanic activity took place hundreds of millions of years ago, not so recently as was first supposed. This leads to a picture of a planet whose evolution toward a tectonically active Earthlike body has run its course, arrested in its infancy by an insufficient supply of internal heat. The latter presumably is traceable to the initial chemical constitution of the planet.

It is clear from the evidence on hand that the Moon and Mercury have been quiescent since the formation of marelike smooth plains shortly after the cessation of heavy bombardment. Mercury, unlike the Moon, appears to have gone through a tectonic phase of sorts, i.e., crustal shortening. This occurred quite early, during the bombardment epoch, and probably represents a simple crustal adjustment to a slight shrinking of the large Hermian core. As far as can be gathered today, the planet-building process stopped about 3.5 billion years ago as the episodic period of bombardment ended and the inner Solar System was cleared of much of its debris. After that, the individual planets were on their own; they evolved from the materials then within them.

The past decade of planetary exploration has provided mankind with a completely new view of the inner planets which has reflected into our view of the Earth. Planetology has developed into a comparative science in which the broader viewpoint of accurate information concerning all the terrestrial planets—even though still fragmentary—is allowing scientists to take a much harder look at many aspects of Earth sciences—geology, geophysics, climatology and even meteorology. While currently we by no means know all there is to know about how the planets were formed, speculations are based on direct knowledge, knowledge that could never be gained by remote observations from Earth.

Our shiny, fragile spacecraft have given us a perspective totally unavailable to the greatest scientists of the past. Planetary exploration is essentially a cultured activity—a creature and indicator of the level and nature of our civilization. Kenneth Clark, standing on the Pont des Arts in Paris, regarding the Institute of France, the Louvre and Notre Dame, speculated on the definition of civilization, saying "what is civilization? I don't know...But I think I can recognize it when I see it." In Mariner 10 and its views of little known worlds, we can recognize an element of our own.

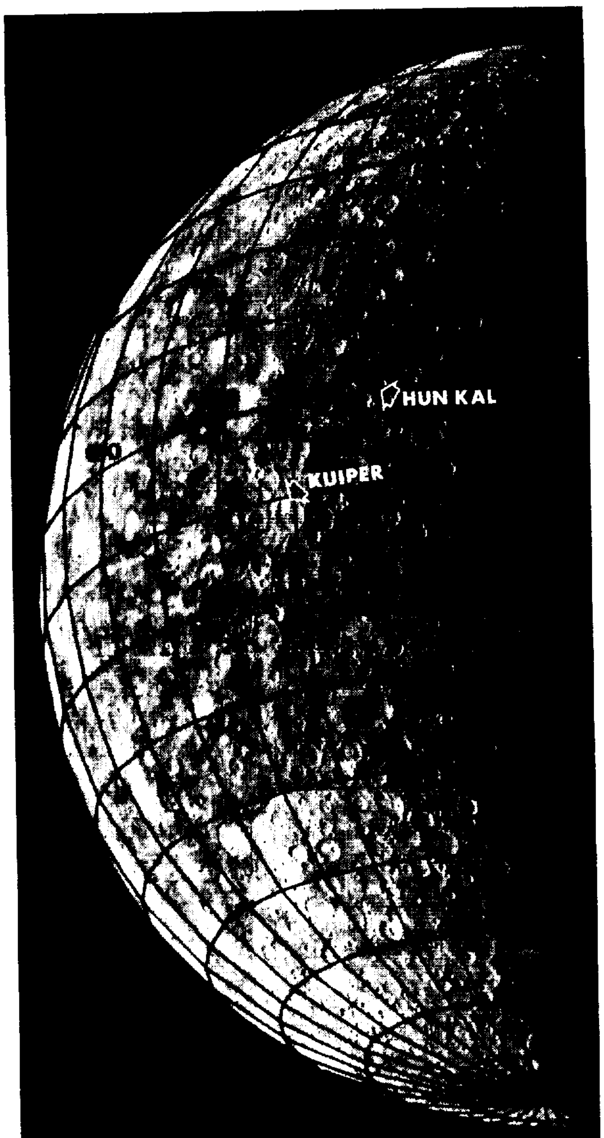
David Morrison, reporting in the scientific journal *Icarus* in the First International Colloquium on Mercury held at Caltech in 1975, stated "This Colloquium demonstrated the degree to which Mariner 10 observations have plucked Mercury from obscurity, so that now data on this planet are providing important input to discussions of the origin and early chemical and dynamical evolution of the solar system as well as to theories of planetary surfaces and interiors...it seems certain that the Mariner data will continue to be analyzed for many years to come, and that this planet is now firmly fixed in both public and scientific consciousness as a real world, as interesting and unique as is each of the other planets."

Appendix A Mercury Mosaics and Maps

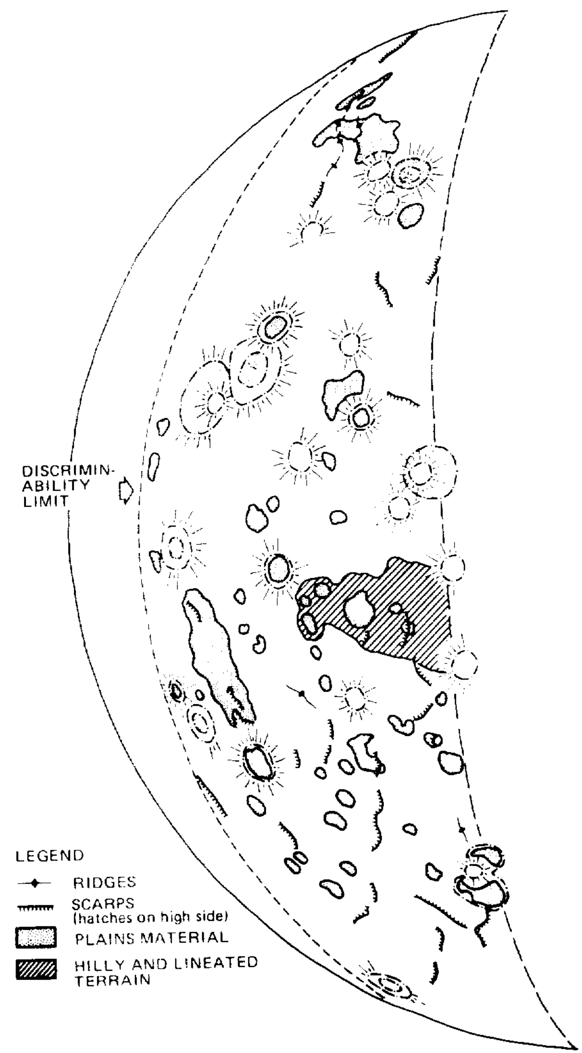
This appendix presents mosaics of Mercury made from images obtained during the second flyby, September 21, 1974, when Mariner 10's closest approach was 50,000 km (30,000 mi) over the sunlit hemisphere. These mosaics link the two mosaics obtained during the first encounter to provide a total coverage of 45% of the illuminated hemisphere at useful viewing angles. The series of mosaics taken at the second encounter include several of the same areas of Mercury seen from different viewing angles. During the third encounter, imaging concentrated on high-resolution pictures of areas of interest. Some of the results are included in this appendix and compared with views taken during the earlier encounters.

Some unique stereo pairs of areas of Mercury which can easily be viewed with a simple mirror to provide an astronaut's impression of the surface of the innermost planet of the solar system are also included here.

Fig. A-1. Eighteen pictures, taken at 42-sec intervals by Mariner 10's two TV cameras, were computer-enhanced and assembled by hand into this photomosaic. The pictures were taken during a 13-min period when Mariner was 200,000 km (124,000 mi) from Mercury on March 29, 1974, and was rapidly approaching the planet. Latitude and longitude references for the figure are given in (a); (b) identifies some of the geological features. Kuiper was the first marking recognizable on the Mariner pictures taken during the approach to Mercury. Hun Kal is the reference crater for latitude and longitude on Mercury, almost on the equator at 20 degrees longitude (see Fig. A-3). North is at the top, and the Sun is illuminating the planet from the left.



(a)



(b)

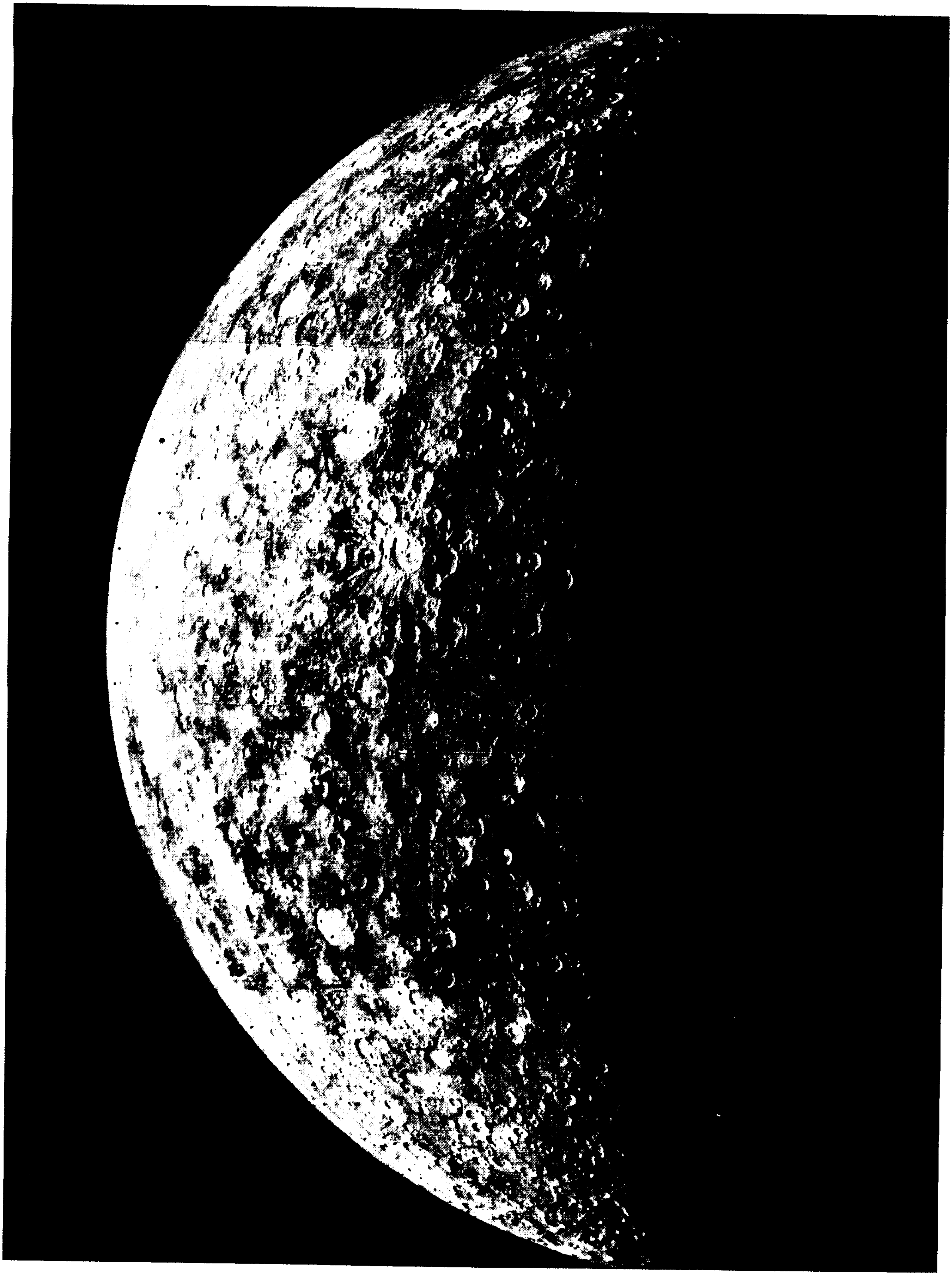
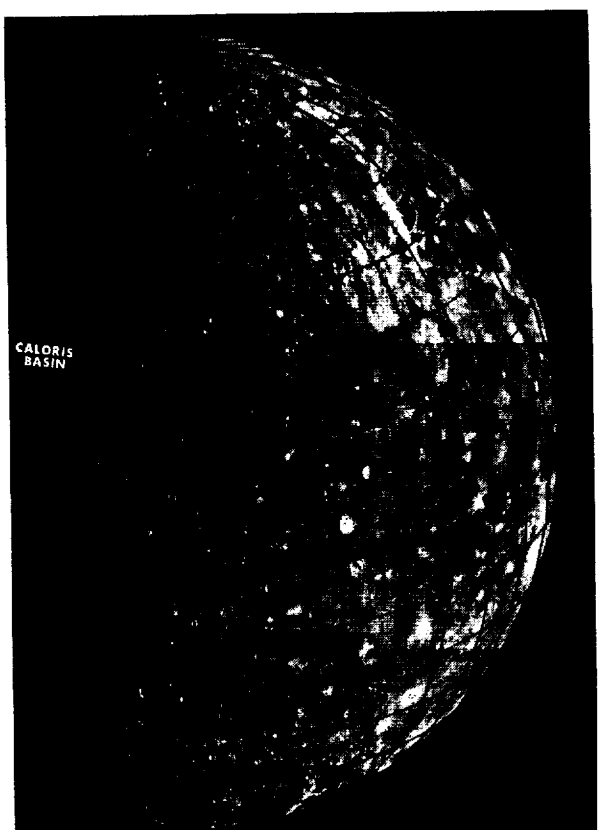
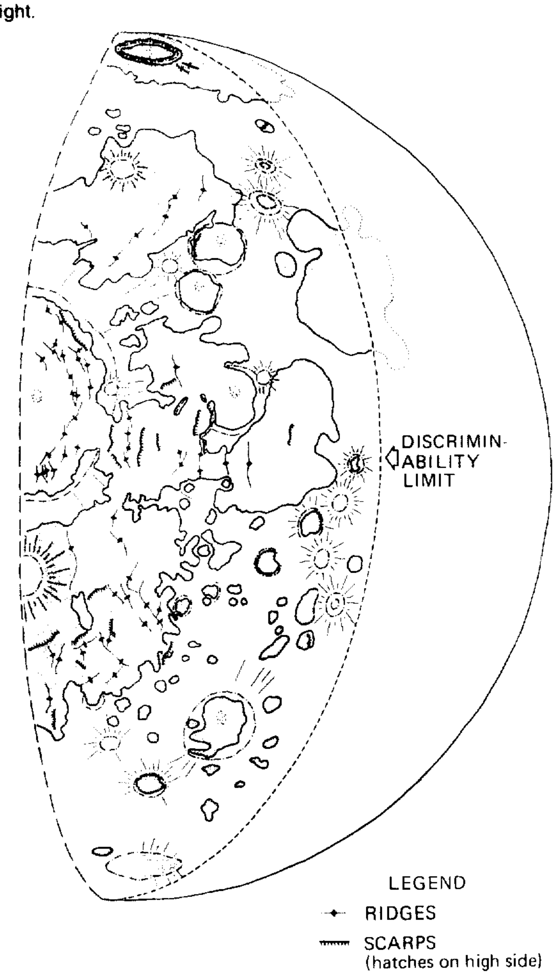


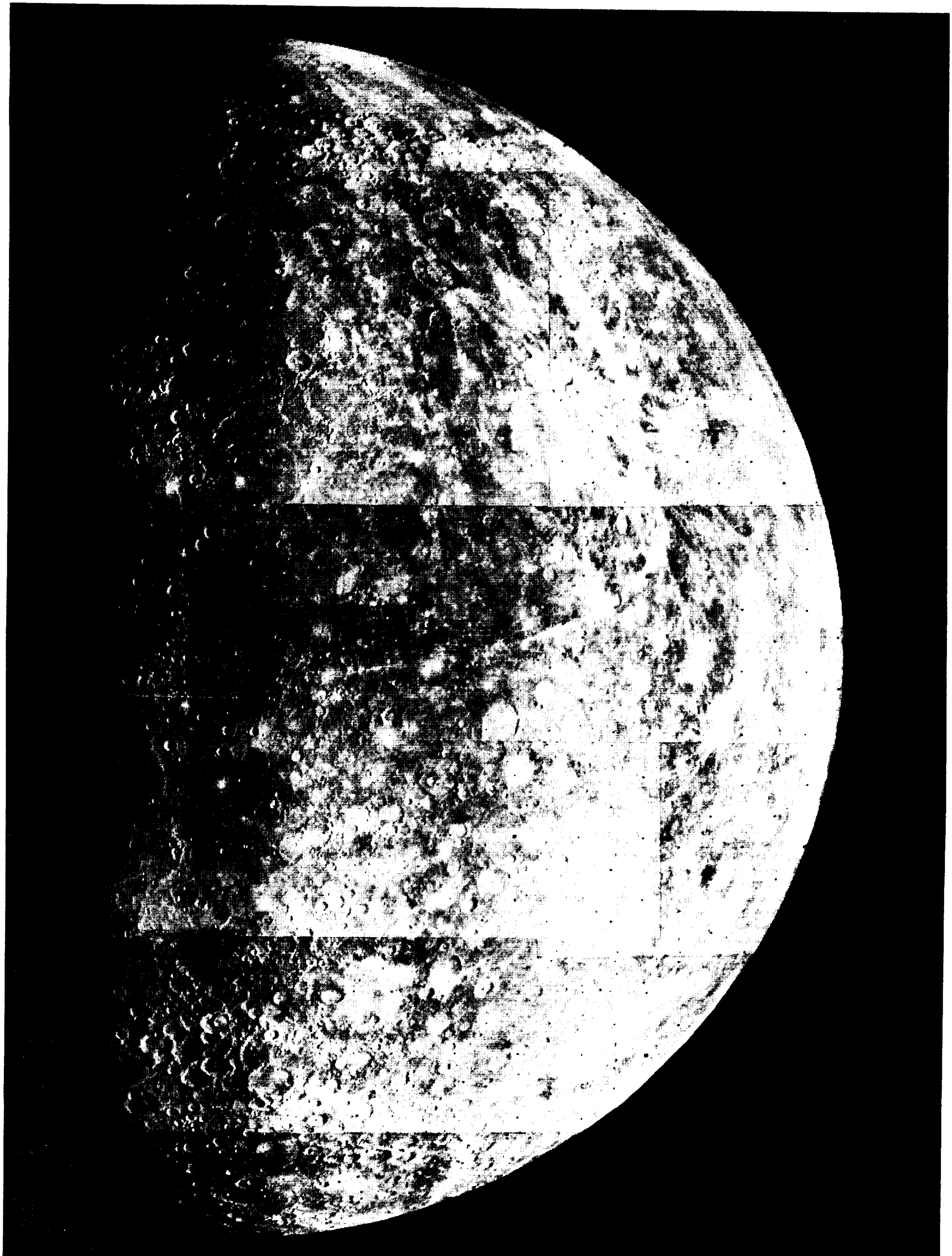
Fig. A-2. This photomosaic of Mercury was constructed of 18 photos taken at 42-sec intervals by Mariner 10 six hours after the spacecraft flew past the planet on March 29, 1974. A large circular basin about 1300 km (800 mi) in diameter straddles the terminator. This is Caloris. Bright-rayed craters are prominent in this view of the planet. The pictures were taken from a distance of 210,000 km (130,000 mi). In (a) latitude and longitude references for the mosaic are provided, and (b) identifies some of the geological features. Again, north is at the top, and the Sun is shining on the planet from the right.



(a)



(b)



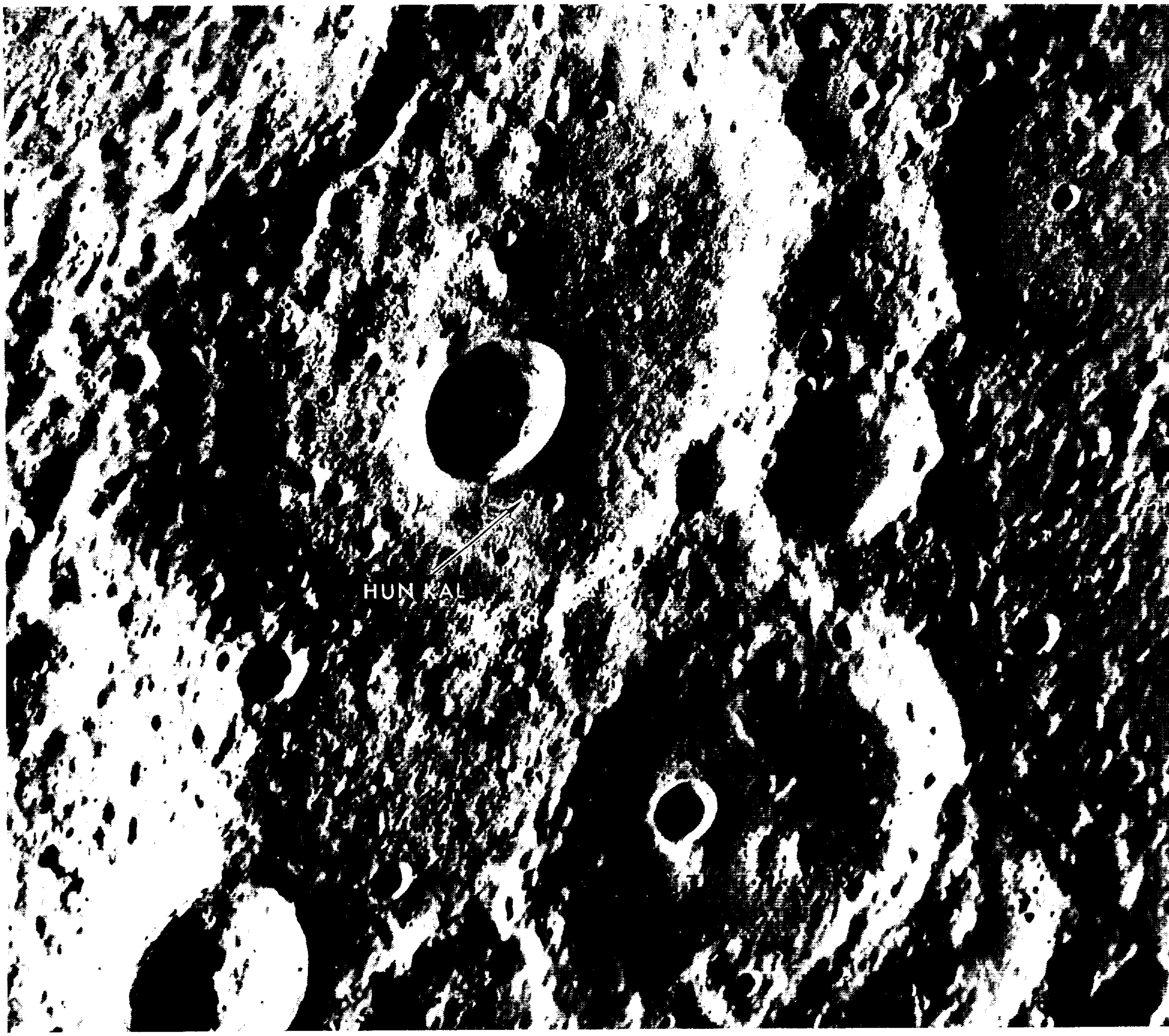


Fig. A-3. A fresh new crater in the center of an older crater basin provides a landmark for the tiny crater named Hun Kal—the Mayan number 20—which is the basis for positioning the longitudes on Mercury. By definition, the 20° meridian passes through the center of this small crater. Assuming that the spin axis of Mercury is perpendicular to its orbital plane, the latitude of Hun Kal is 0.23°S. This picture, which covers an area of 130 by 170 km (90 by 105 mi), was taken from a distance of about 20,700 km (12,860 mi), a half-hour before Mariner made its first close flyby of Mercury, March 1974.

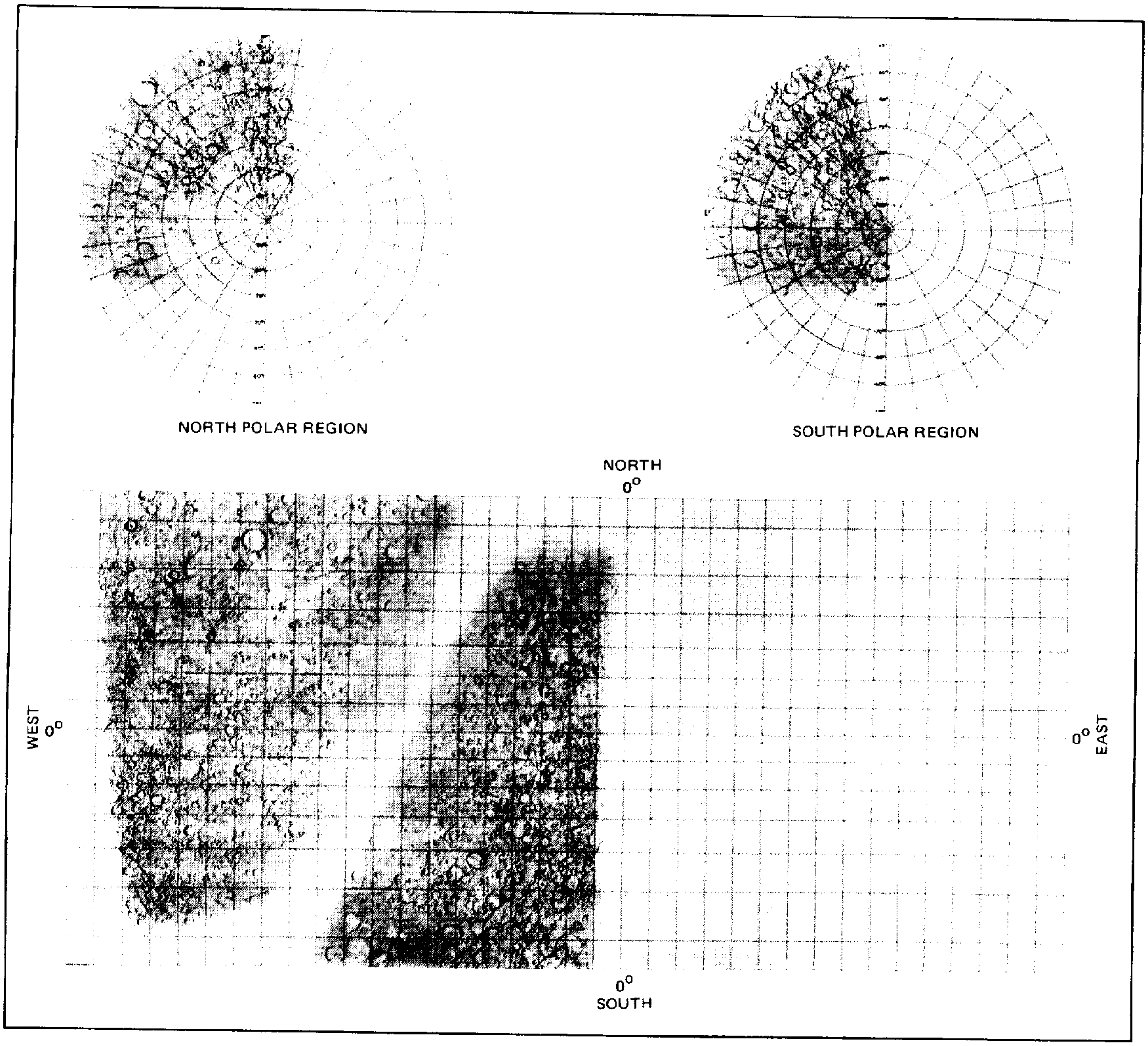
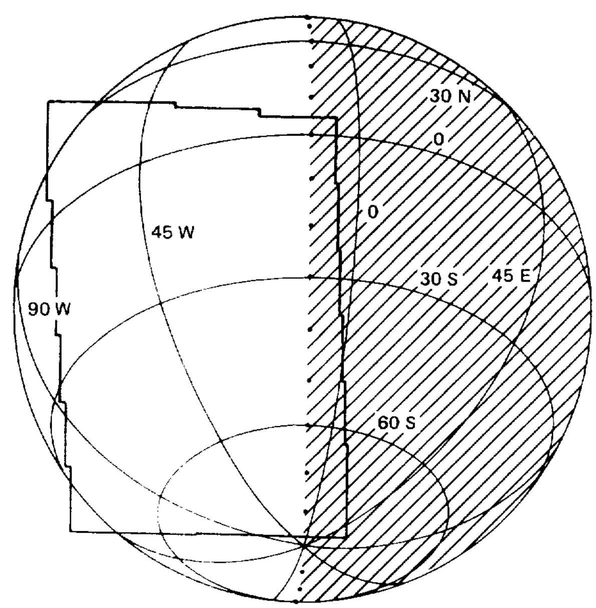


Fig. A-4. From the photomosaics obtained by Mariner, the U.S. Geological Survey is preparing an atlas of Mercury. A control net of Mercury has been established together with coordinates of over 1000 points from the Mariner 10 photographs. The series of maps of Mercury will be produced at a scale of 1:5,000,000. Topographic and albedo features are portrayed by airbrush techniques similar to an earlier series of maps of the Moon and of Mars. The map reproduced here shows the coverage obtained during Mercury I to a scale of 1:25,000,000. The diagonal gap across the map was, of course, filled in by the photographs obtained later at the second encounter.

Fig. A-5. This first of the mosaics obtained at the second encounter covers much the same area of Mercury as the incoming mosaic of the first encounter but extends farther into south polar regions. The crater Kuiper is clear in the top part of the picture. North is at the top, and the Sun illuminates Mercury from the left. The black areas represent parts of Mercury that were not covered in this mosaic. The line drawing below relates the mosaic to latitude and longitude on the illuminated disc of the planet at the time of the encounter.



TIME FROM CLOSEST APPROACH
0 d 3 h 11 m 48 s

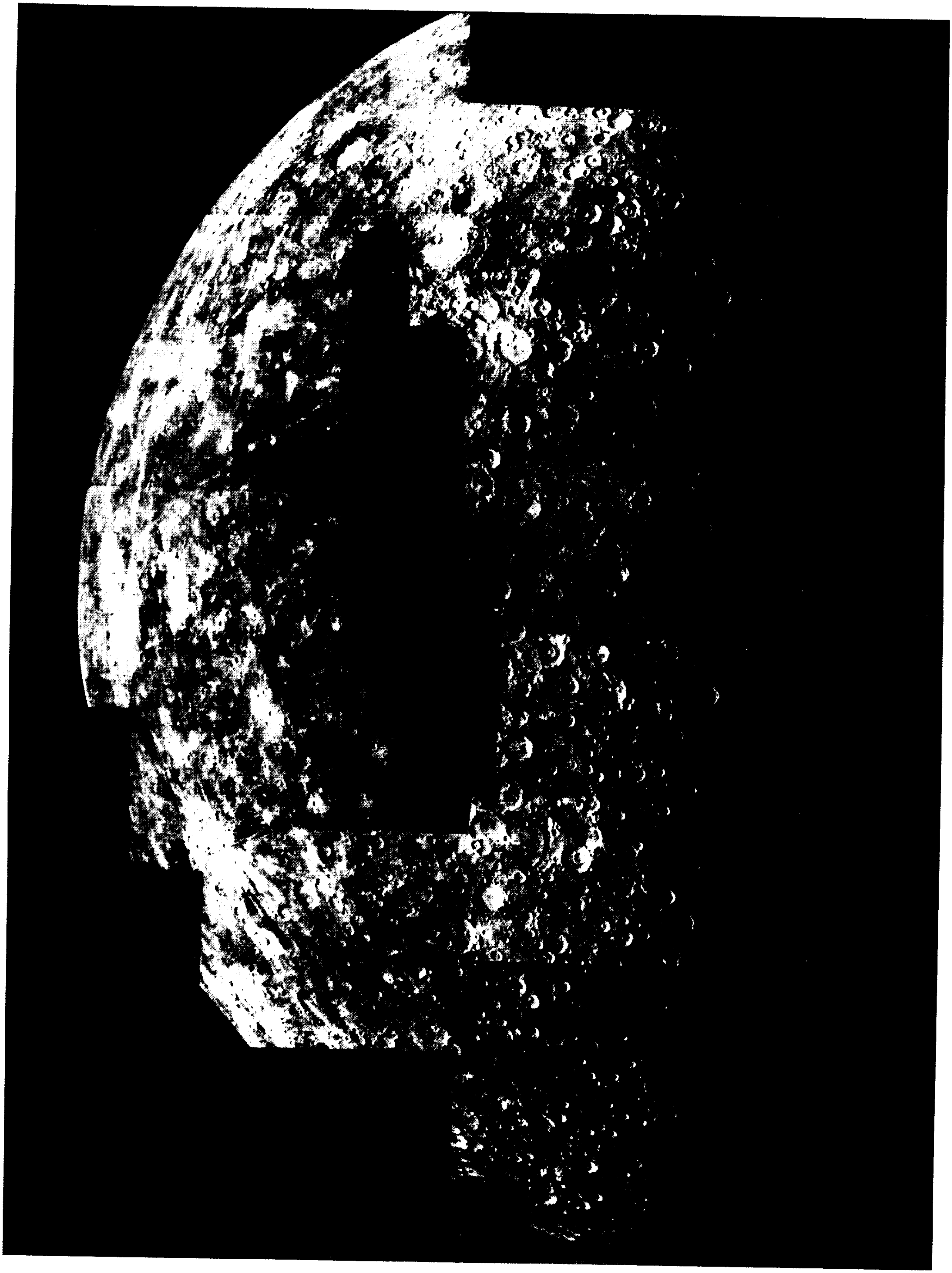
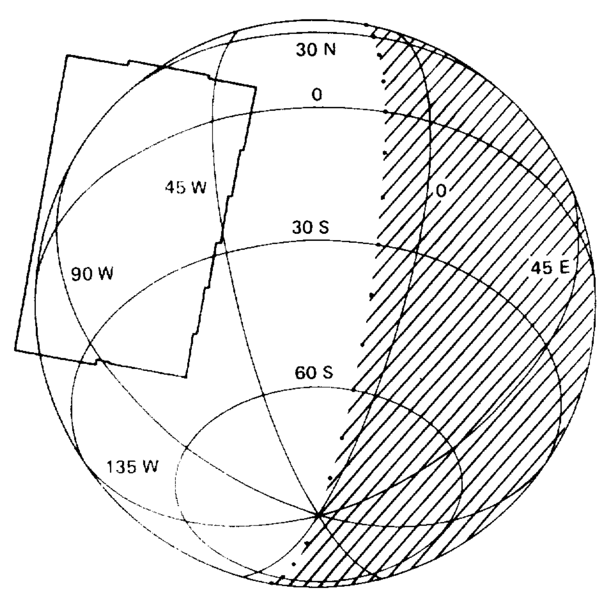
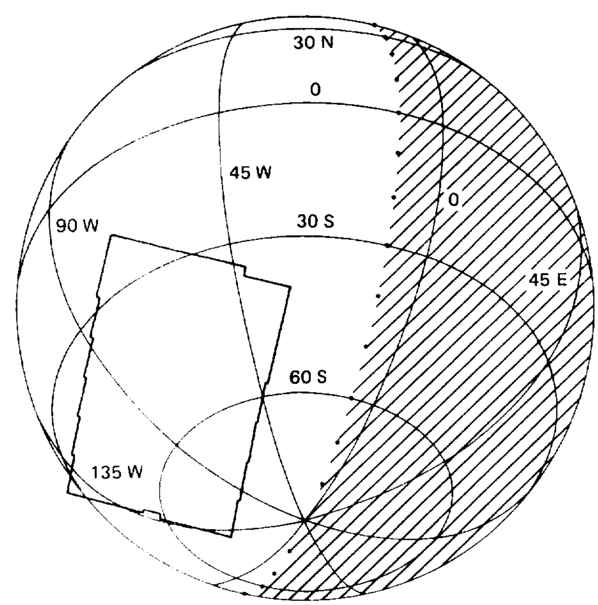


Fig. A-6. The second mosaic swings up toward the limb region. Two bright craters in the lower left quadrant of Fig. A-5 are now placed centrally to the right and immediately below the black area of missing coverage on this mosaic.



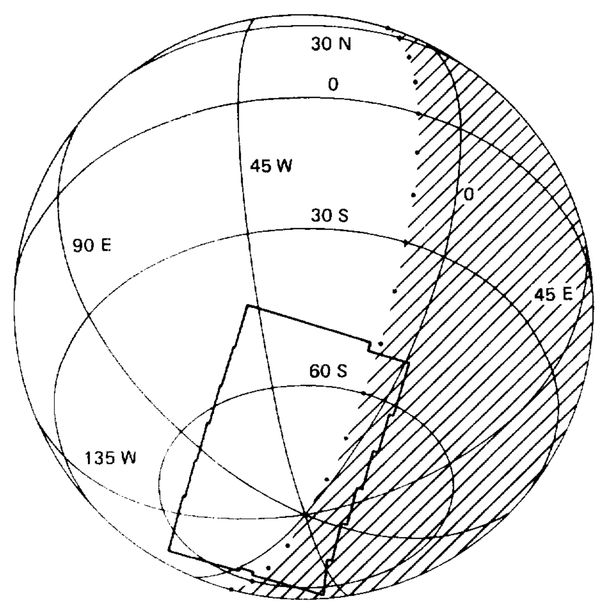
TIME FROM CLOSEST APPROACH
0 d 1 h 57 m 36 s

Fig. A-7. This mosaic covers regions to the south at increasing resolution. The two bright-rayed craters are in the upper left-hand quadrant of this picture. The prominent scarp in the middle of the top half of the picture is named Astrolabe after the ship used by d'Urville in Antarctica in 1838–1840. It is located at 45°S latitude and 70° longitude. A system of bright rays radiates from a crater off the right bottom of the mosaic.



TIME FROM CLOSEST APPROACH
0 d 1 h 45 m 0 s

Fig. A-8. This mosaic covers the southern terminator region. Discovery scarp is at the top center, named after one of Cook's ships on his last voyage to the Pacific during 1776-1780. The south pole of Mercury is located in the large crater with its floor in shadow one-third of the way along the terminator from the bottom of the mosaic.



TIME FROM CLOSEST APPROACH
0 d 1 h 32 m 24 s

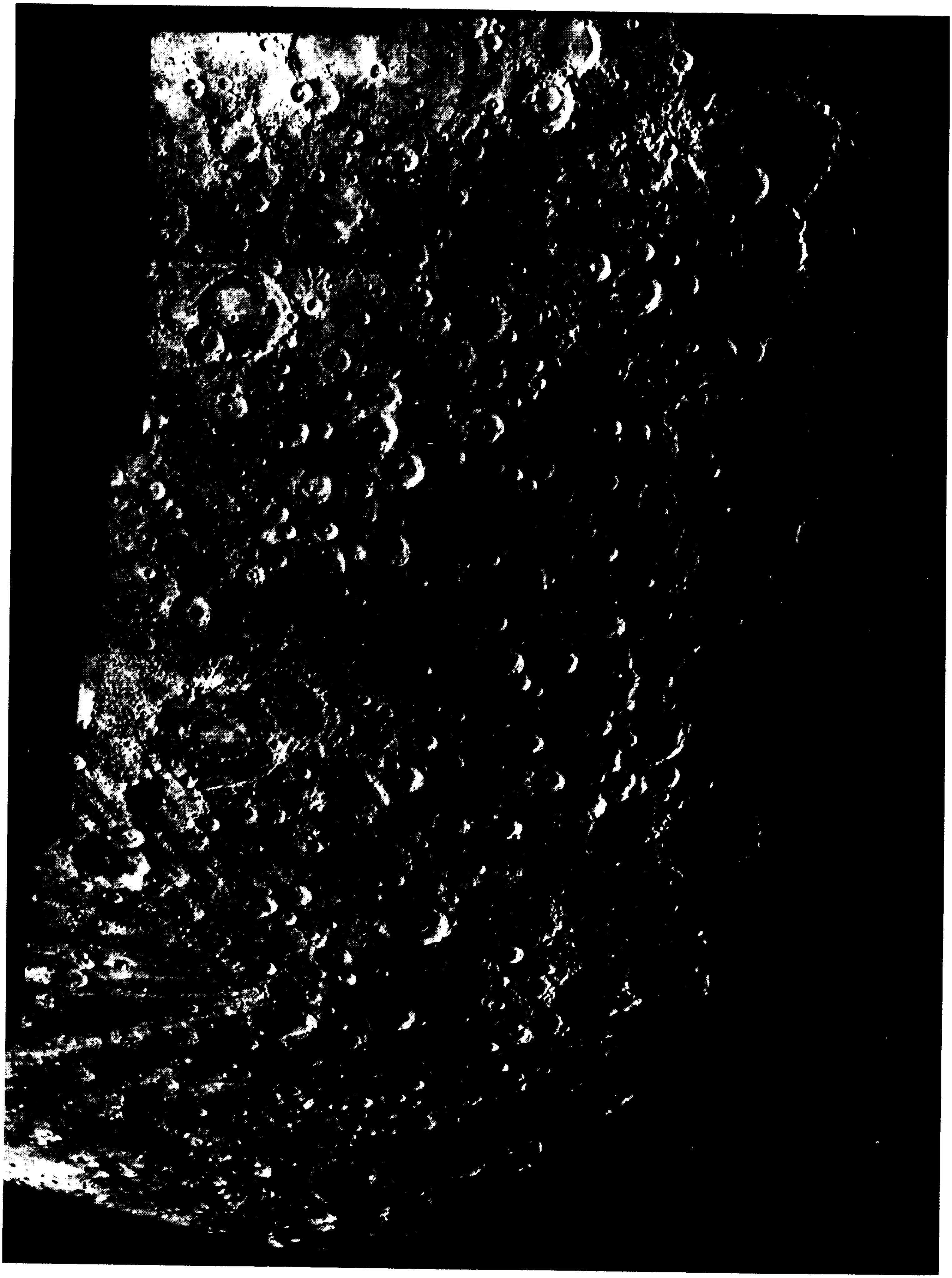
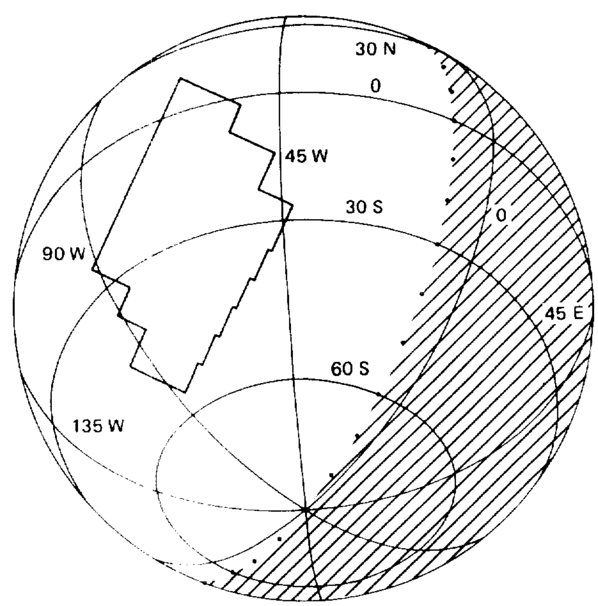


Fig. A-9. Moving northward again, this mosaic is centered about 30°S latitude and 75° longitude. It shows again the twin bright-rayed crater of Figs. A-6 and A-7. The Astrolabe Scarp is one-third the way up the right-hand edge of the mosaic.



TIME FROM CLOSEST APPROACH
0 d 1 h 15 m 36 s

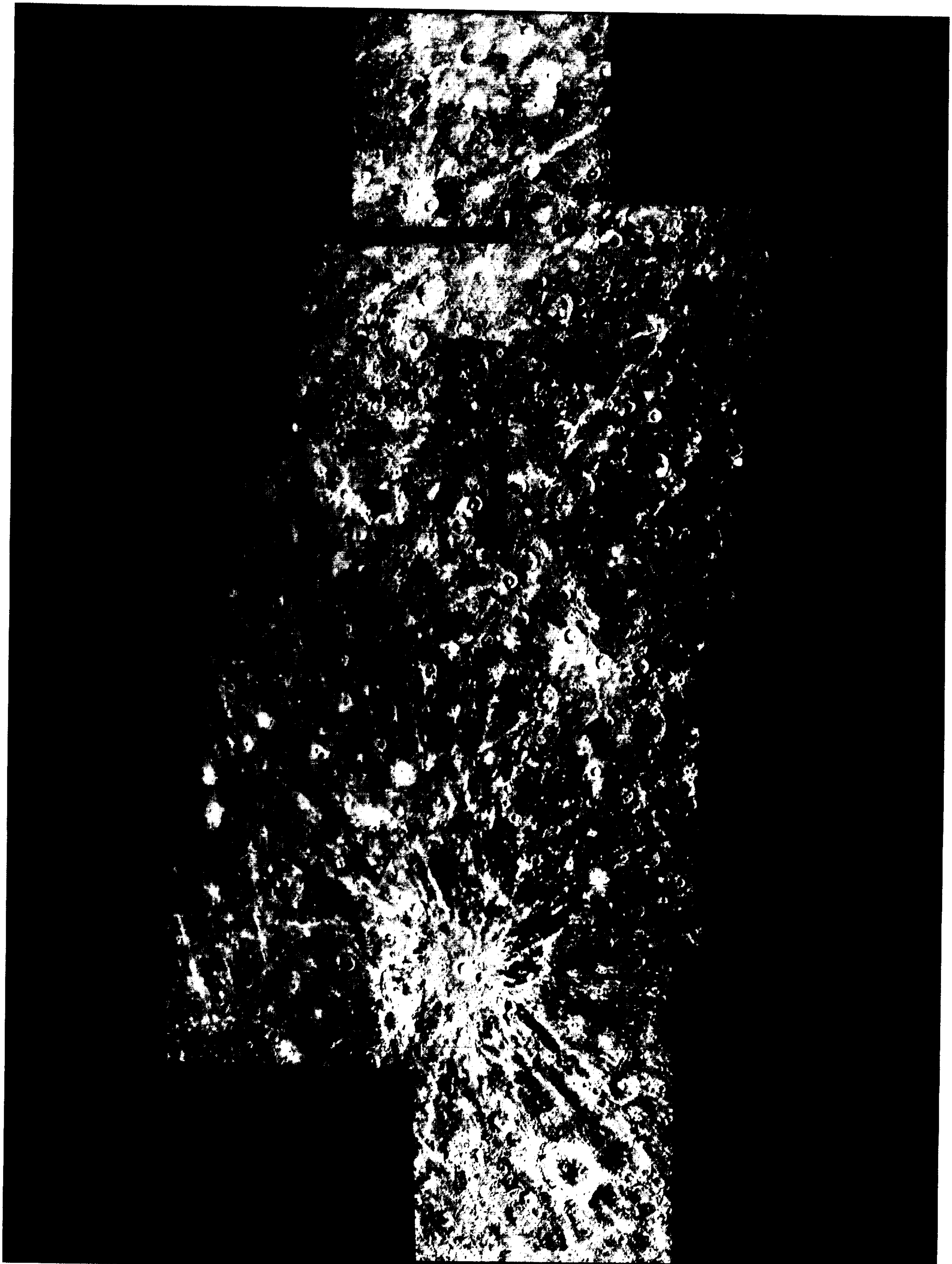
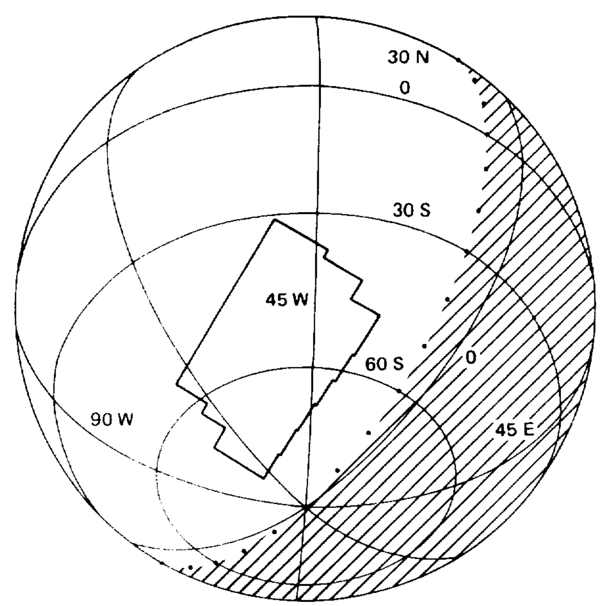
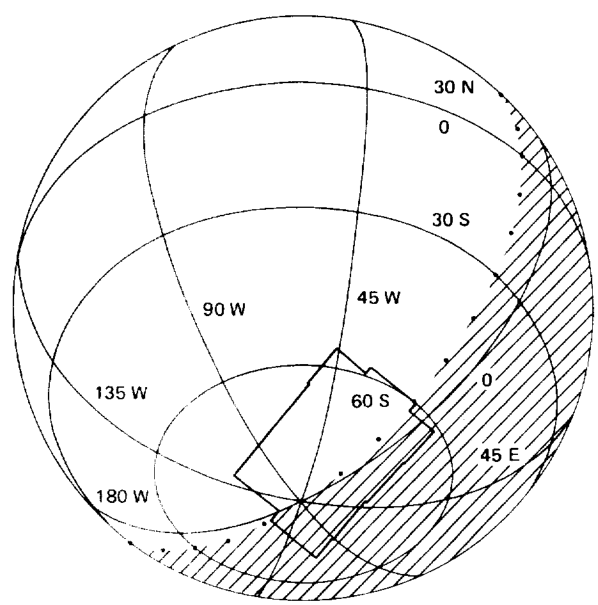


Fig. A-10. This mosaic extends to the southeast of the twin bright-rayed crater of Fig. A-9. Increasing resolution shows a wealth of fine structural detail of the planet's surface.



TIME FROM CLOSEST APPROACH
0 d 1 h 3 m 0 s

Fig. A-11. Continuing southward, this mosaic shows the south polar region in great detail; the south pole of Mercury is within the shadowed crater one-quarter of the way from the bottom of the right-hand edge of the mosaic. Two mountain tops gleam as tiny spots within the crater. Three large double-ring basins are between 150 and 200 km in diameter. Alongside them, smooth plains contain many ridges and scarps.



TIME FROM CLOSEST APPROACH
0 d 0 h 50 m 24 s

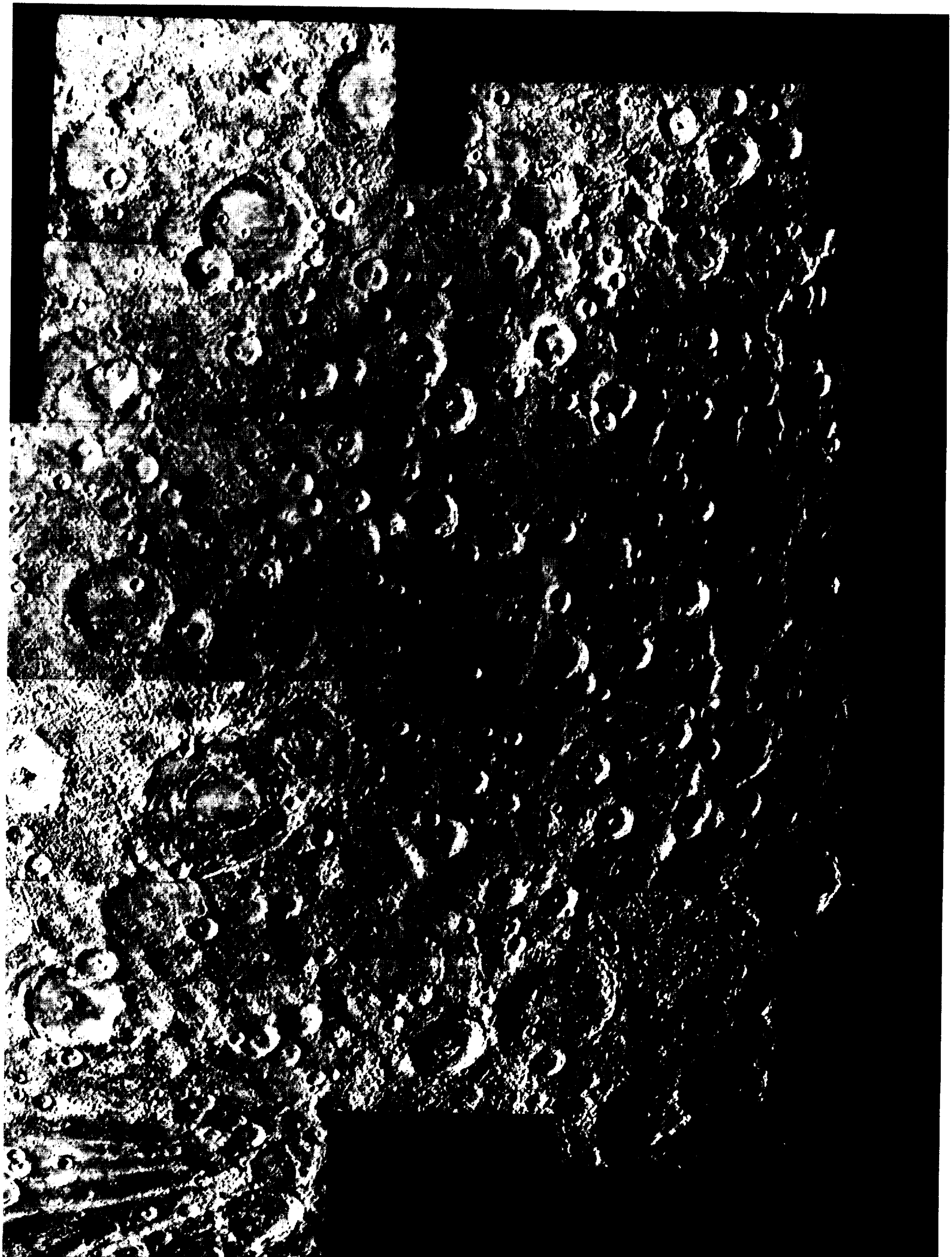
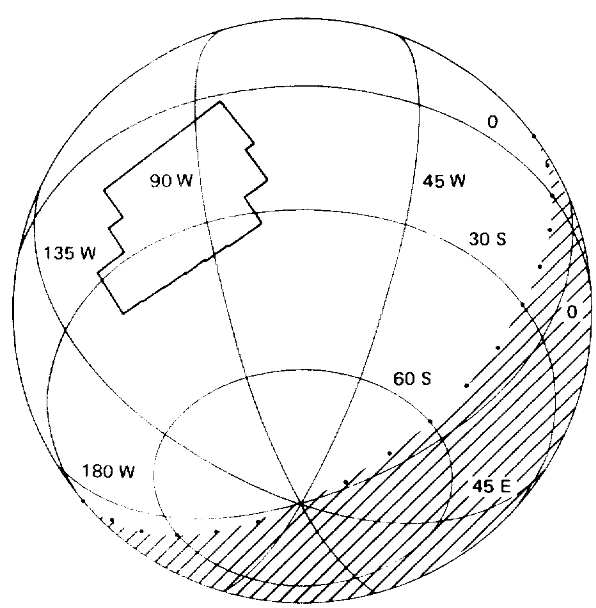


Fig. A-12. As Mariner flies by the planet it looks at a part of the surface on which the sun is shining from overhead. Craters and mountains cast no visible shadows and surface features are seen as albedo differences, light rings of crater walls, streaks, rays, and light and dark splotches. The center of this mosaic is approximately 90° longitude and 20°S latitude.



TIME FROM CLOSEST APPROACH
0 d 0 h 37 m 48 s

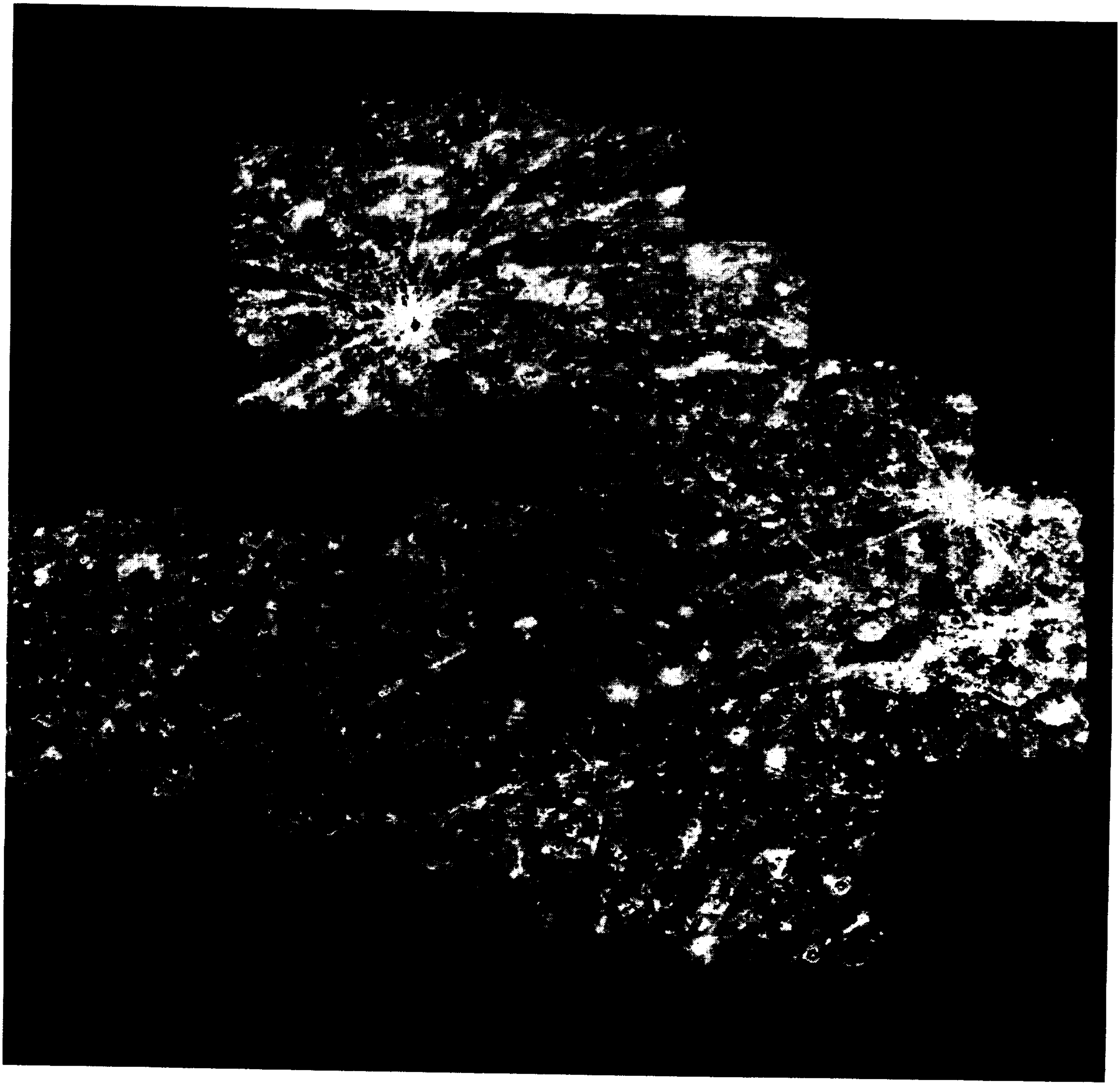
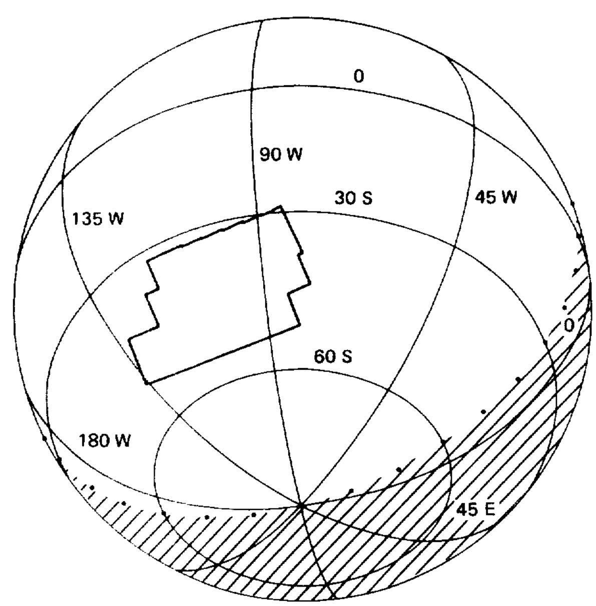


Fig. A-13. This mosaic is centered about 100° longitude and 40°S latitude. Somewhat closer to the terminator, it provides more shadow detail than the previous mosaic. The area includes some large crater rings with very rugged surrounding terrain and one very prominent double ring that is almost an impact basin.



TIME FROM CLOSEST APPROACH
0 d 0 h 25 m 12 s

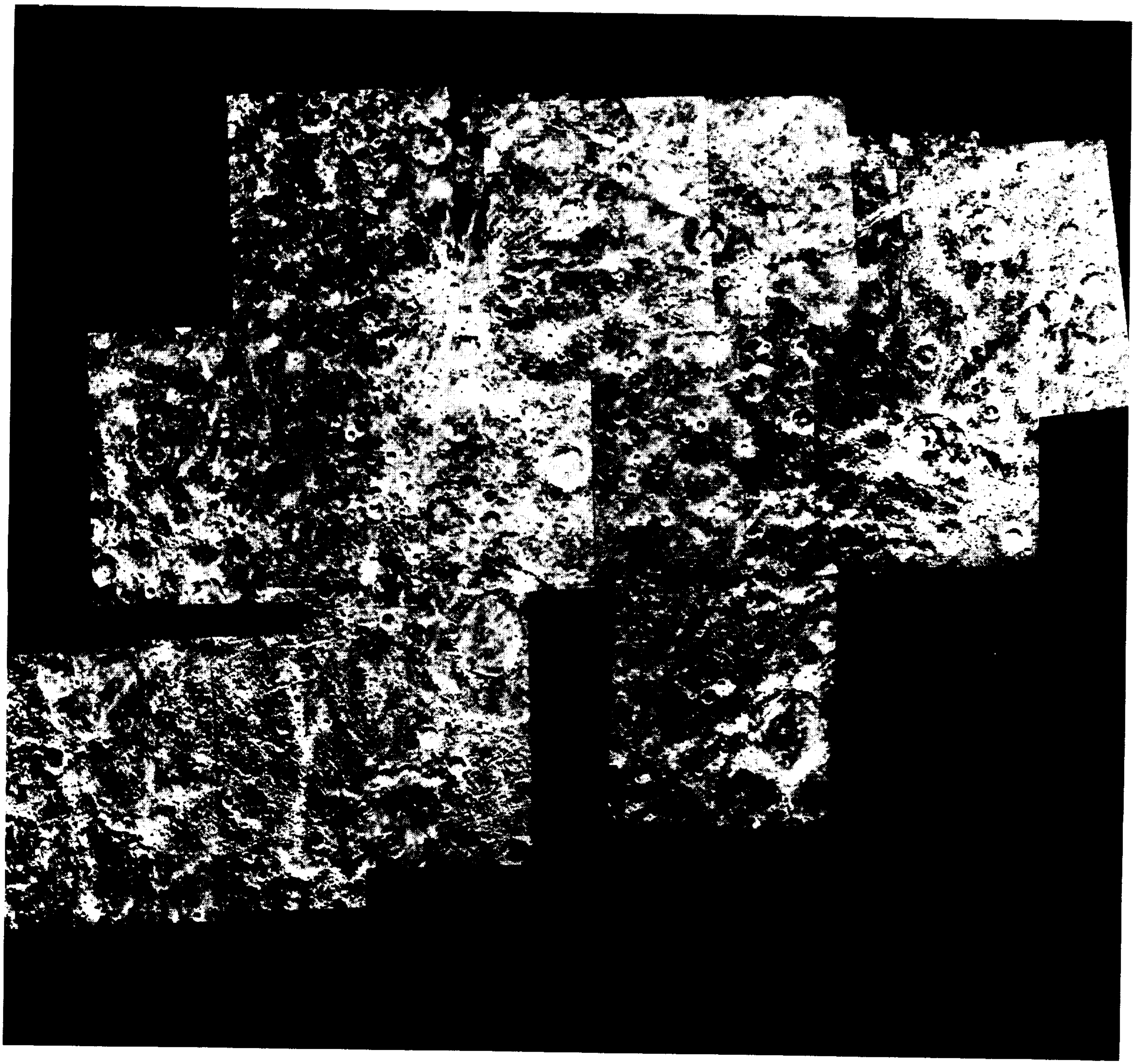
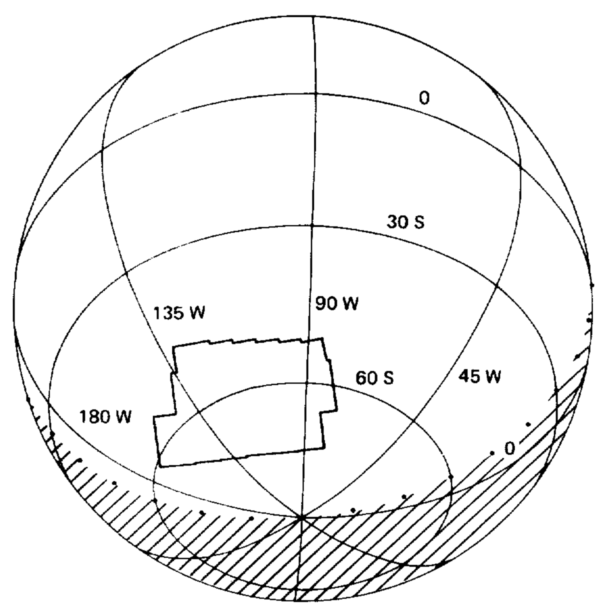


Fig. A-14. An area a little farther south abuts on the previous mosaic. Its center is at 100° longitude and 60°S latitude. The ray systems in the left half of this mosaic can be traced upward into the lower left of Fig. A-13, where there is a very slight overlap of the two mosaics. The prominent bright, large crater with its huge central peak is about 100 km in diameter. Near to it is the large 200-km-diameter double-ring crater, the largest of the three such craters in Fig. A-11 on which the bright, large crater also appears.



TIME FROM CLOSEST APPROACH
0 d 0 h 12 m 36 s

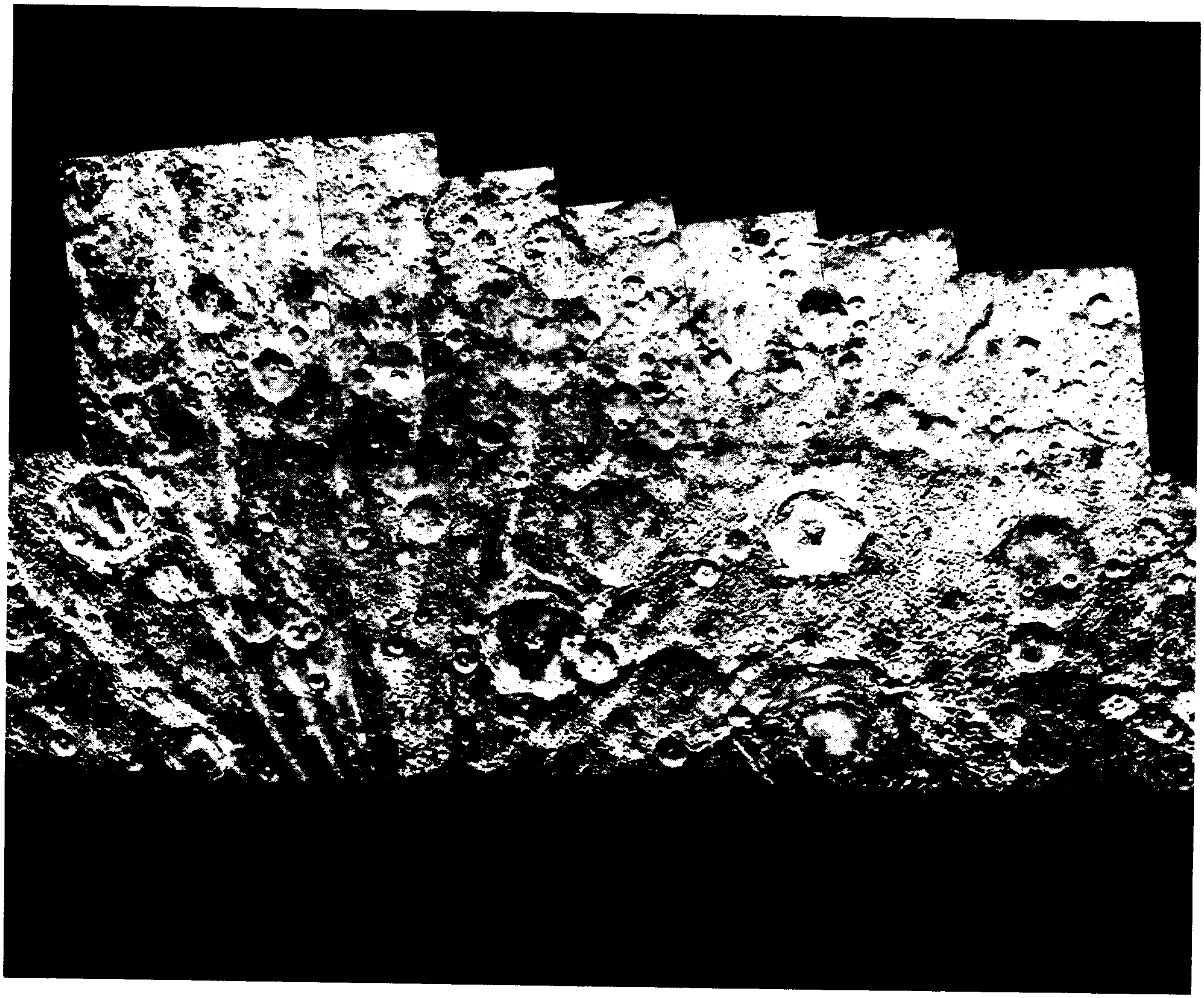
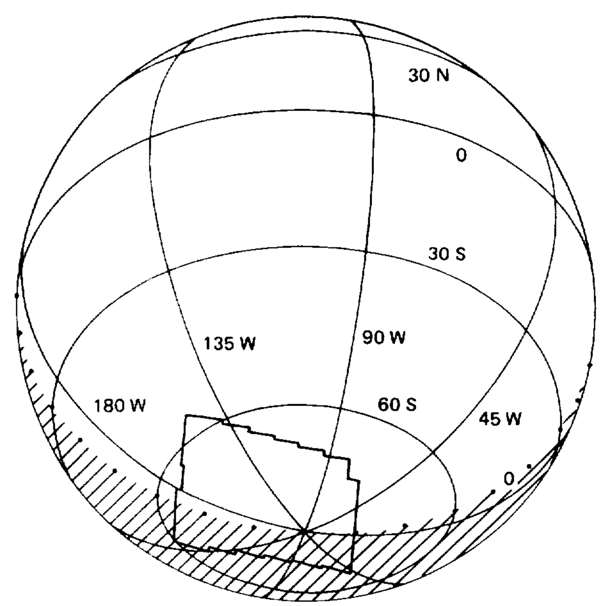


Fig. A-15. Again the mosaic moves south, this time with a little more overlap with the previous mosaic of Fig. A-14. Part of the large double-ringed crater at the bottom of Fig. A-14 can be seen at the top of this mosaic. The origin of the long rays seen in both Figs. A-13 and A-14 is identified in this mosaic as a fresh young crater with a central peak. It is about 50 km in diameter. The two smaller double-ring basins of Fig. A-11 also appear on this figure.



TIME FROM CLOSEST APPROACH
0 d 0 h 0 m 0 s

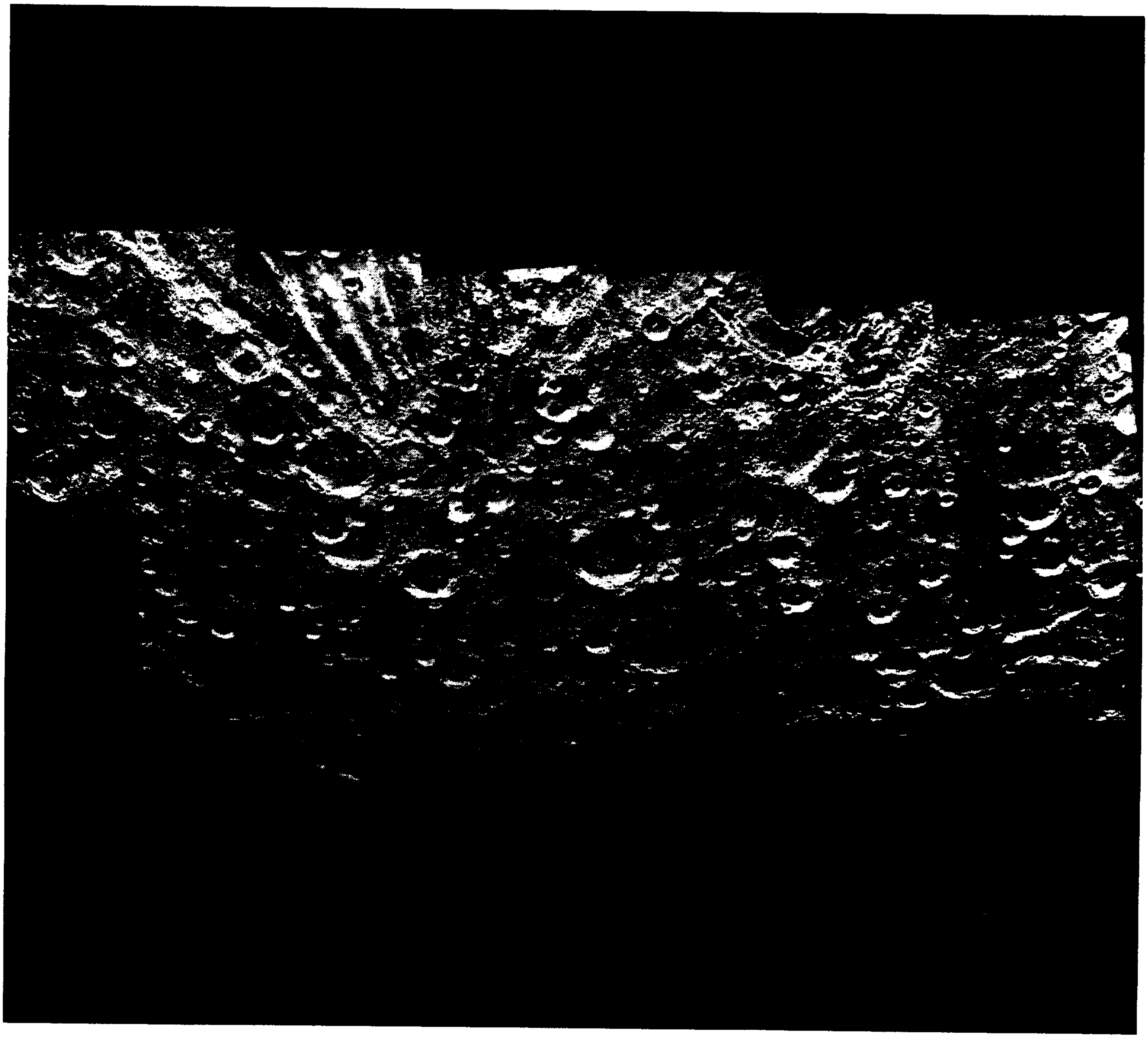
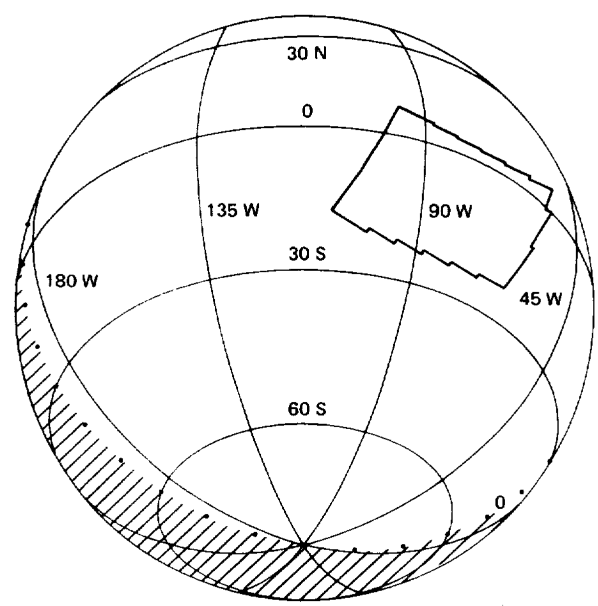


Fig. A-16. Returning to the sun-drenched landscape near to the equator at 80° longitude, this mosaic reveals a criss-crossing area of light streaks from ray craters. This whole area was foreshortened near the limb of the planet as seen in the two mosaics of Mercury I encounter.



TIME FROM CLOSEST APPROACH
0 d 0 h 12 m 36 s

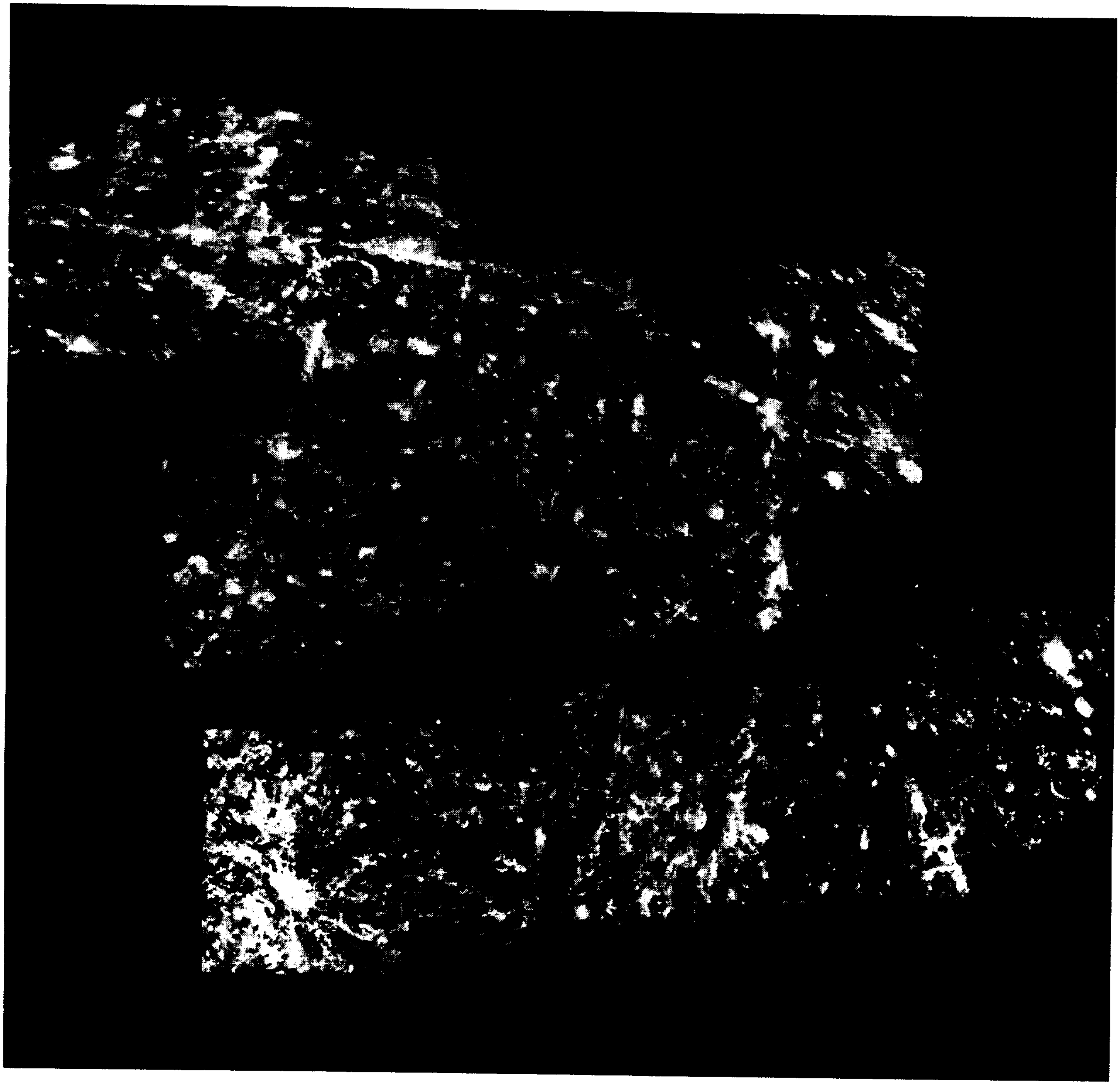
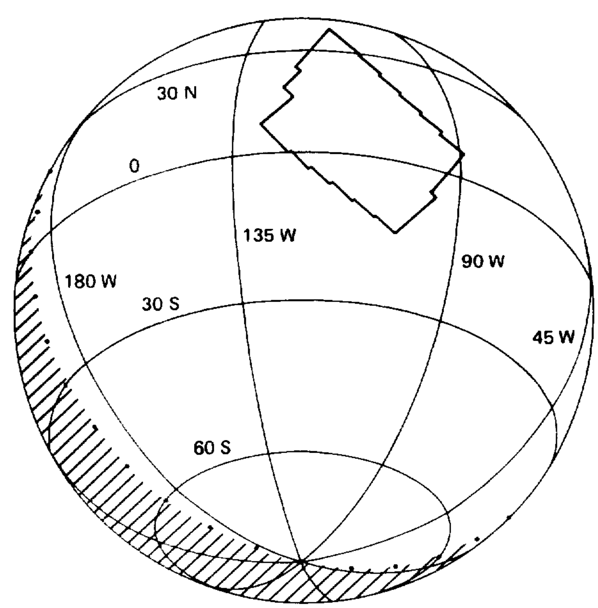


Fig. A-17. Another area close to the limb regions of the incoming and outgoing mosaics of the first encounter is shown here in a region centered just north of the equator at longitude 110°. There is slight overlap with Fig. A-16. The small irregular dark splotch at the top left of Fig. A-16 (close to a bright crater) is near to the bottom right corner of this mosaic.



TIME FROM CLOSEST APPROACH
0 d 0 h 25 m 12 s

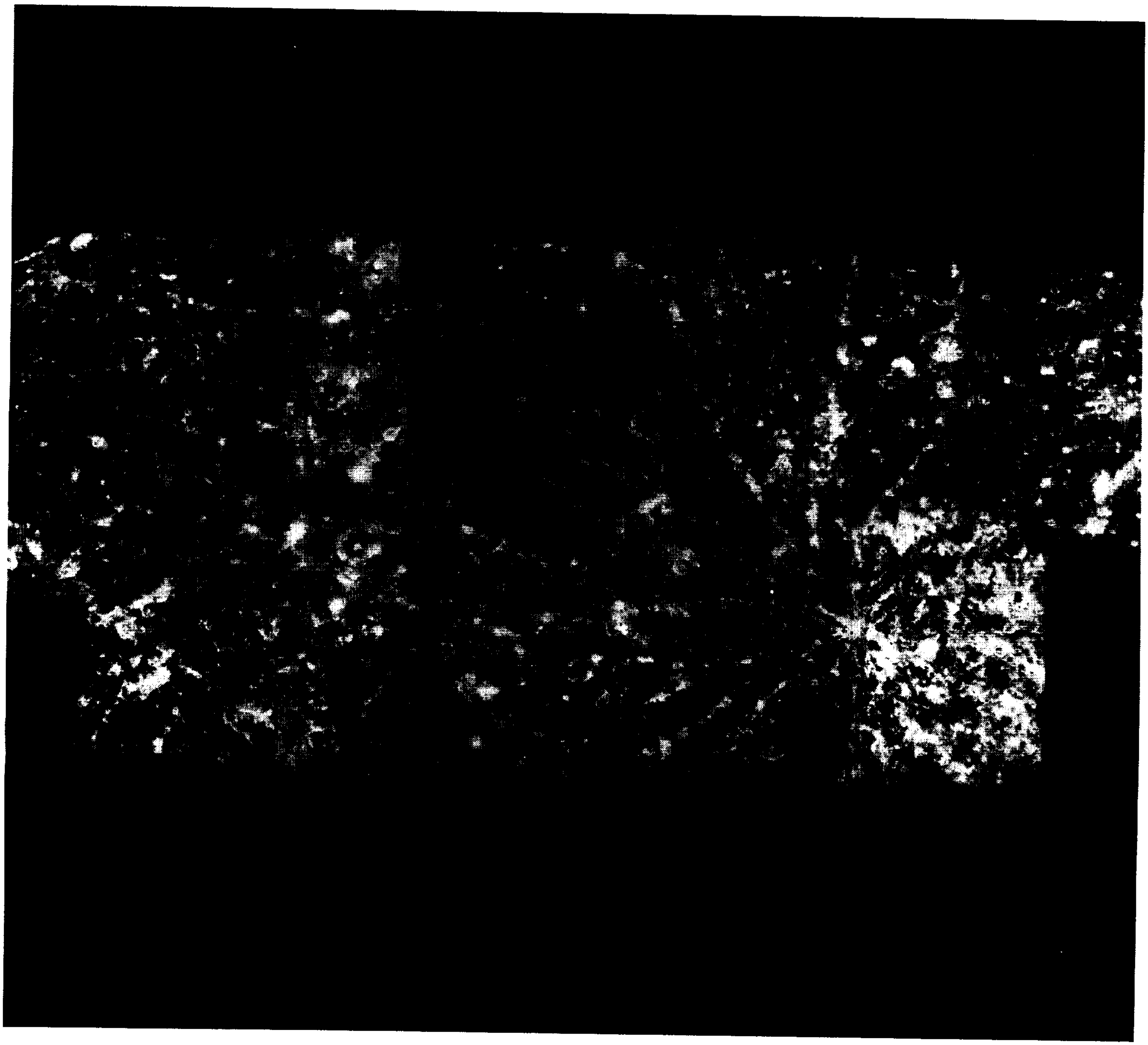
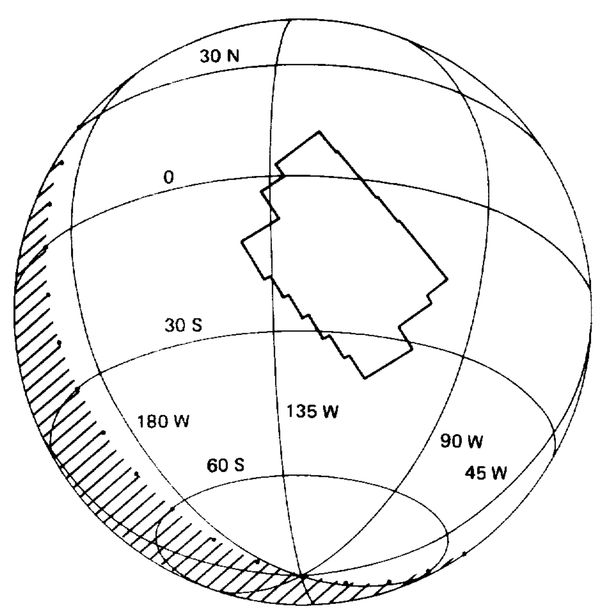


Fig. A-18. This mosaic covers an area to the east of A-17; the bright ray crater bottom right of A-17 is top left on this mosaic. The mosaic is centered about 125° longitude and 15°S latitude.



TIME FROM CLOSEST APPROACH
0 d 0 h 37 m 48 s

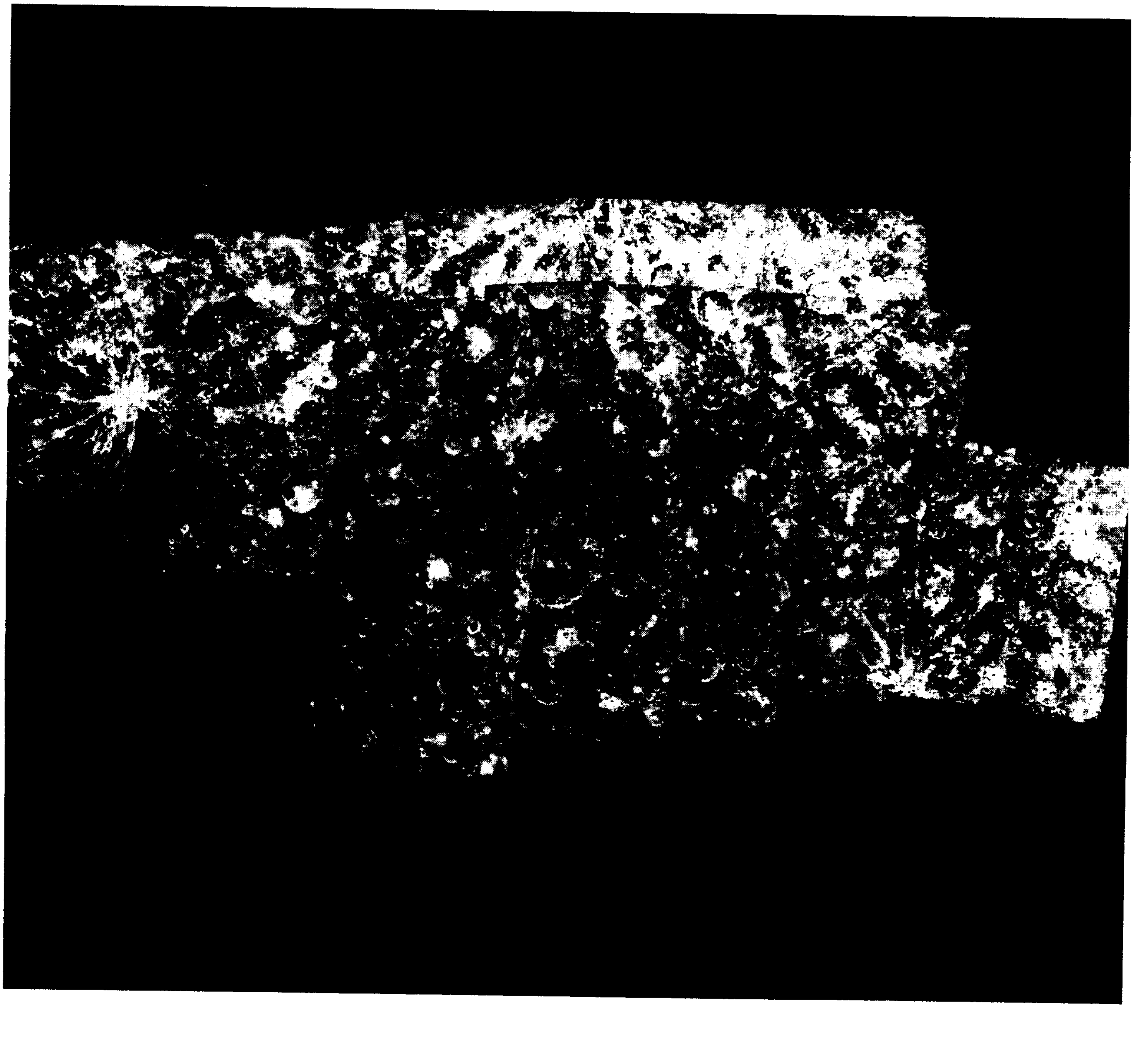
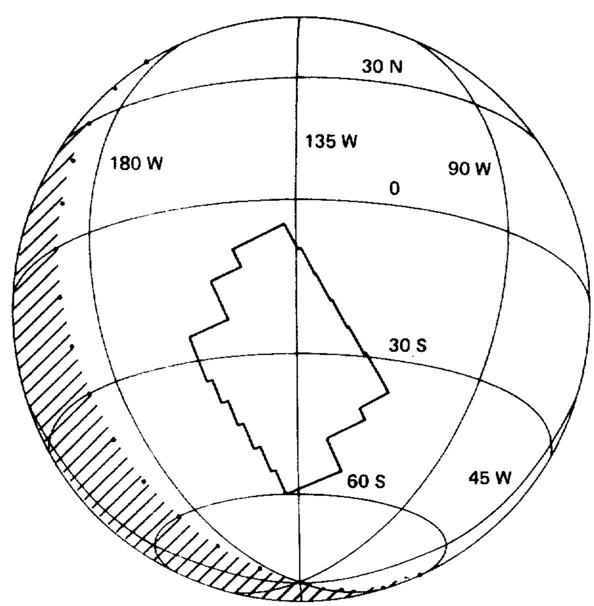


Fig. A-19. Moving its cameras southward and toward the terminator, Mariner 10 took this series for a mosaic centered about 135° longitude and 30°S latitude. The mosaic is dominated by a bright-ringed large crater almost at its center. Just above it is a large basin that shows a ruined inner ring.



TIME FROM CLOSEST APPROACH
0 d 0 h 50 m 24 s

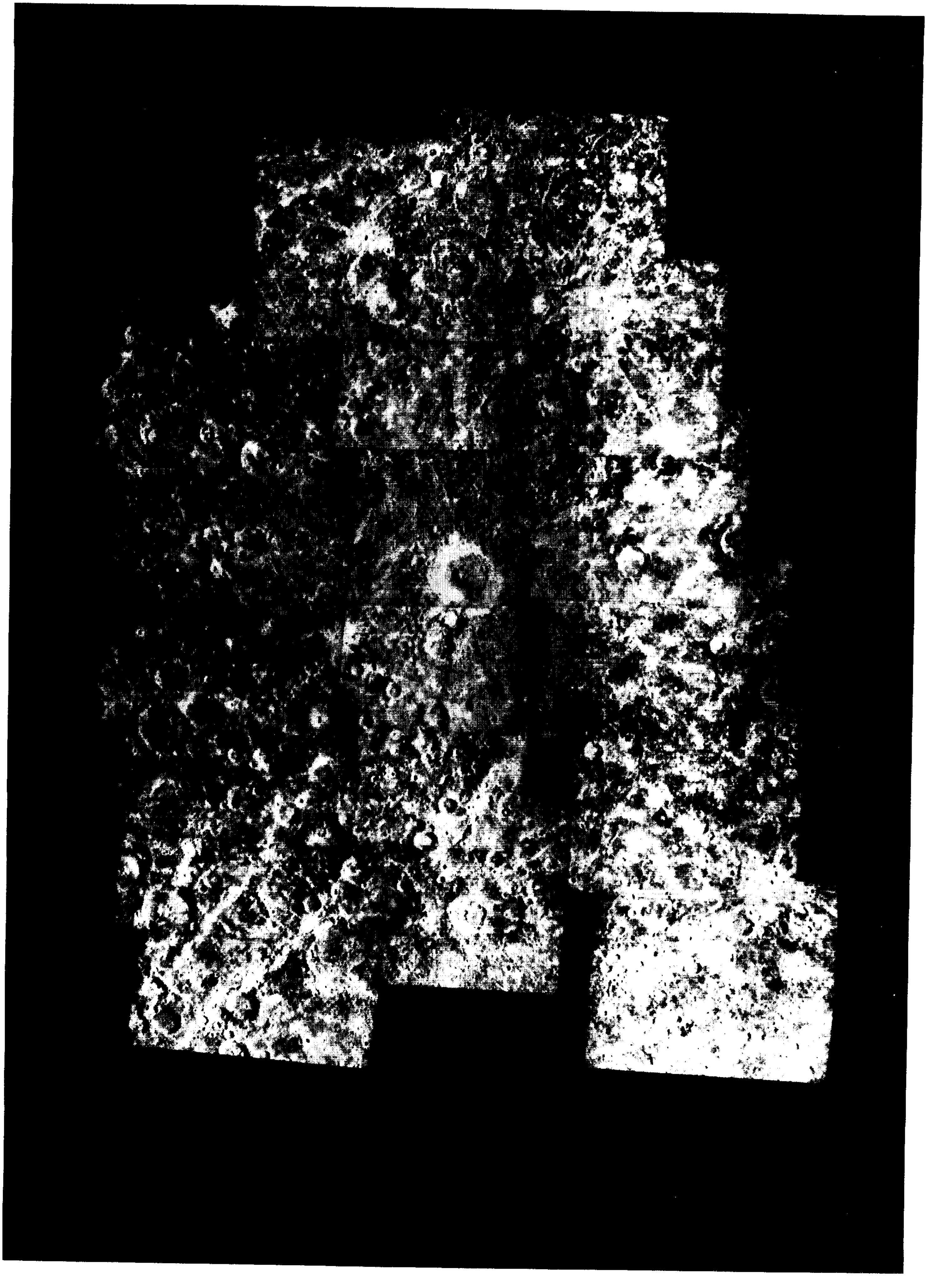
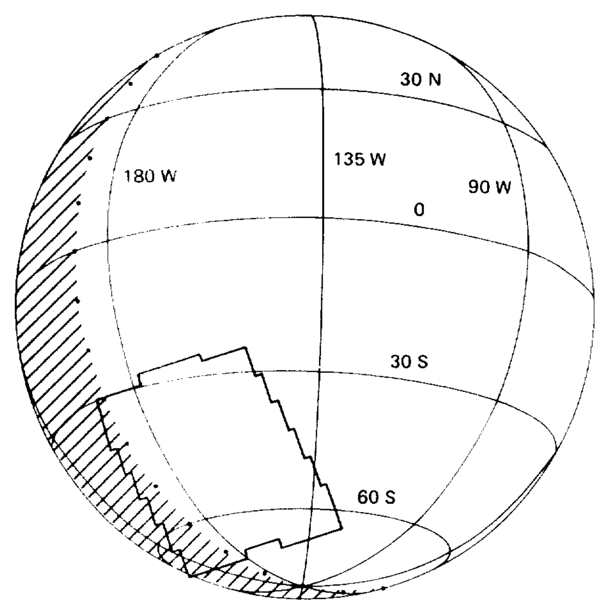


Fig. A-20. South still more and toward the evening terminator, this mosaic shows enormous detail again under low Sun angles. A bright-rayed crater dominates the lower part of the picture. This is the bright-rayed crater of Fig. A-15. North of it and to the west are some unusually long narrow valleys and several prominent scarps. Another young, bright-rayed crater dominates the northern part of this mosaic. There are many large areas of smooth plains material, including a large filled basin marred by subsequent major impacts.



TIME FROM CLOSEST APPROACH
0 d 1 h 3 m 0 s

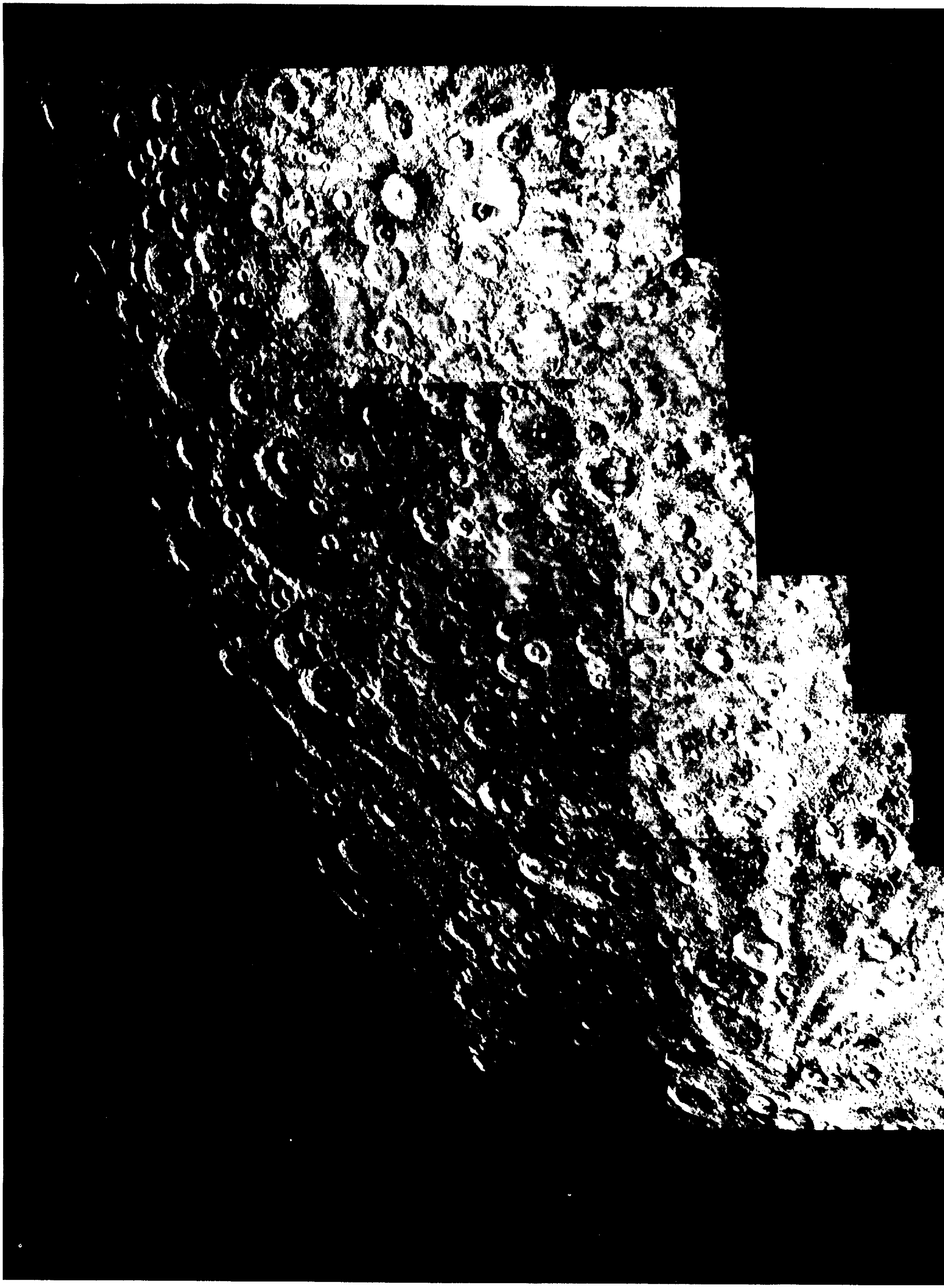
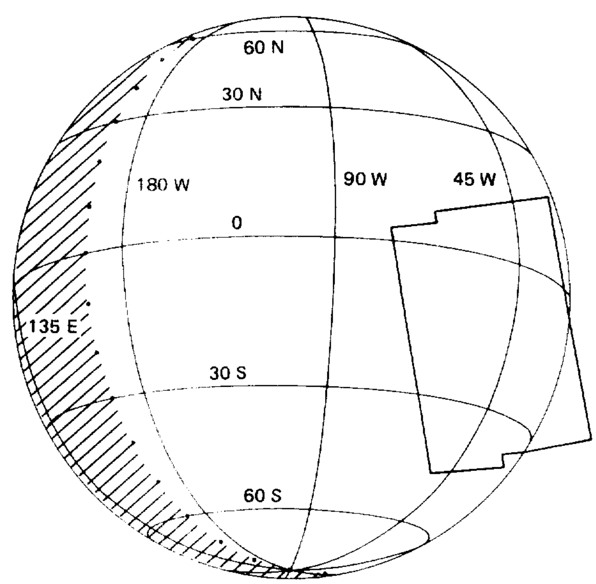
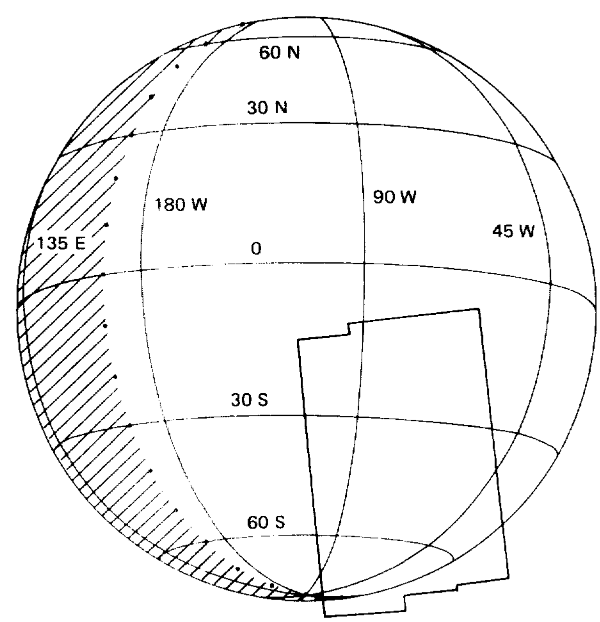


Fig. A-21. Centered about 90° longitude and 15°S latitude, this mosaic shows some of the areas covered earlier but from a different viewpoint. The picture is dominated by albedo markings under a high illumination with virtually no shadow detail.



TIME FROM CLOSEST APPROACH
0 d 1 h 20 m 30 s

Fig. A-22. This mosaic provides details toward the south pole along longitude 120°. Again it is dominated by albedo markings and light rays. The spacecraft was leaving Mercury so that resolution is decreasing.



TIME FROM CLOSEST APPROACH
0 d 1 h 33 m 6 s

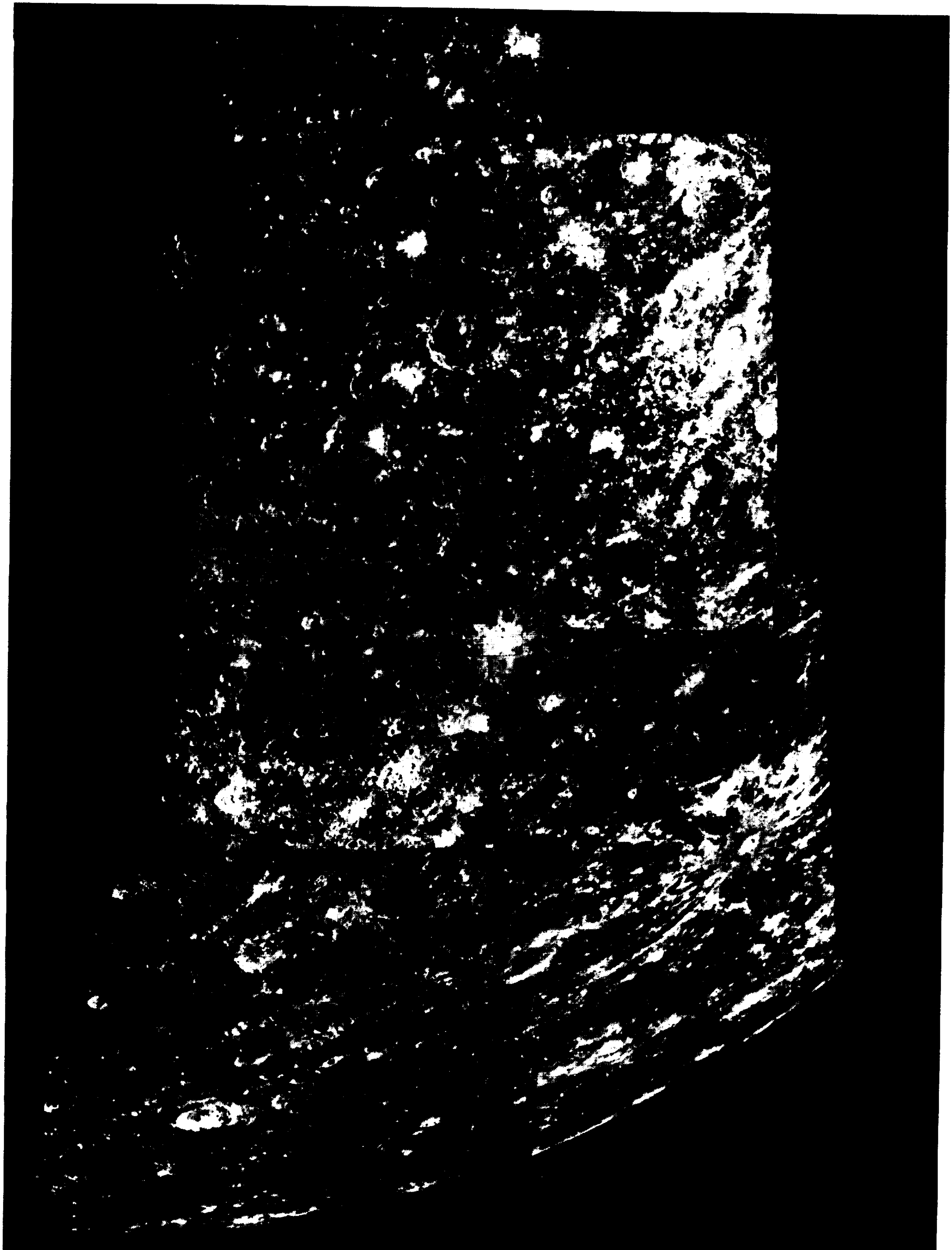
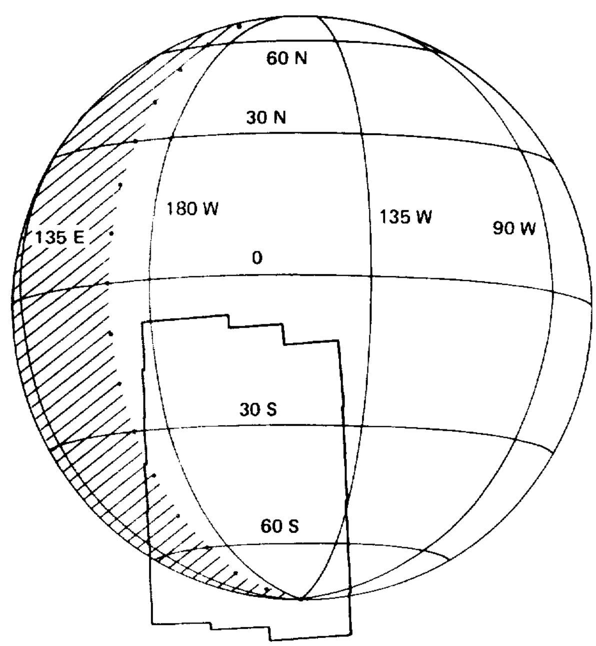
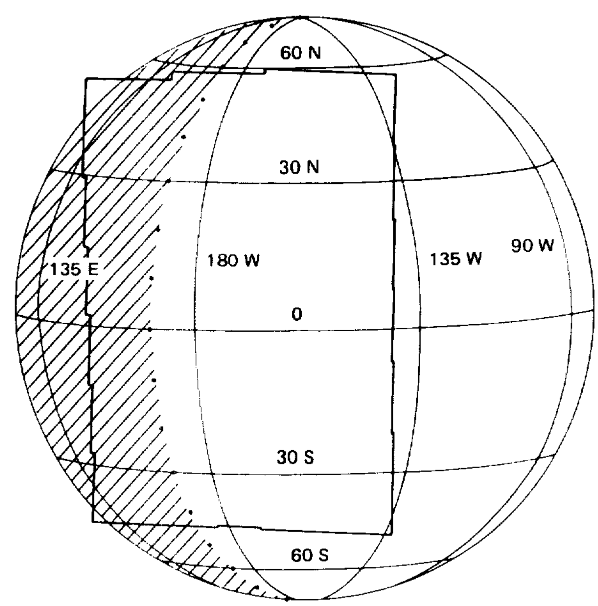


Fig. A-23. The south polar regions are seen here from the opposite side of the planet from Fig. A-11. This mosaic is centered at 160° longitude and 45°S latitude. Close to the right edge of the mosaic is the large crater with its bright rim which is centered in Fig. A-19. Note the bright crater with a central peak and dark halo in the center of the left of the picture. This crater appears at the bottom of the next mosaic but on a smaller scale.

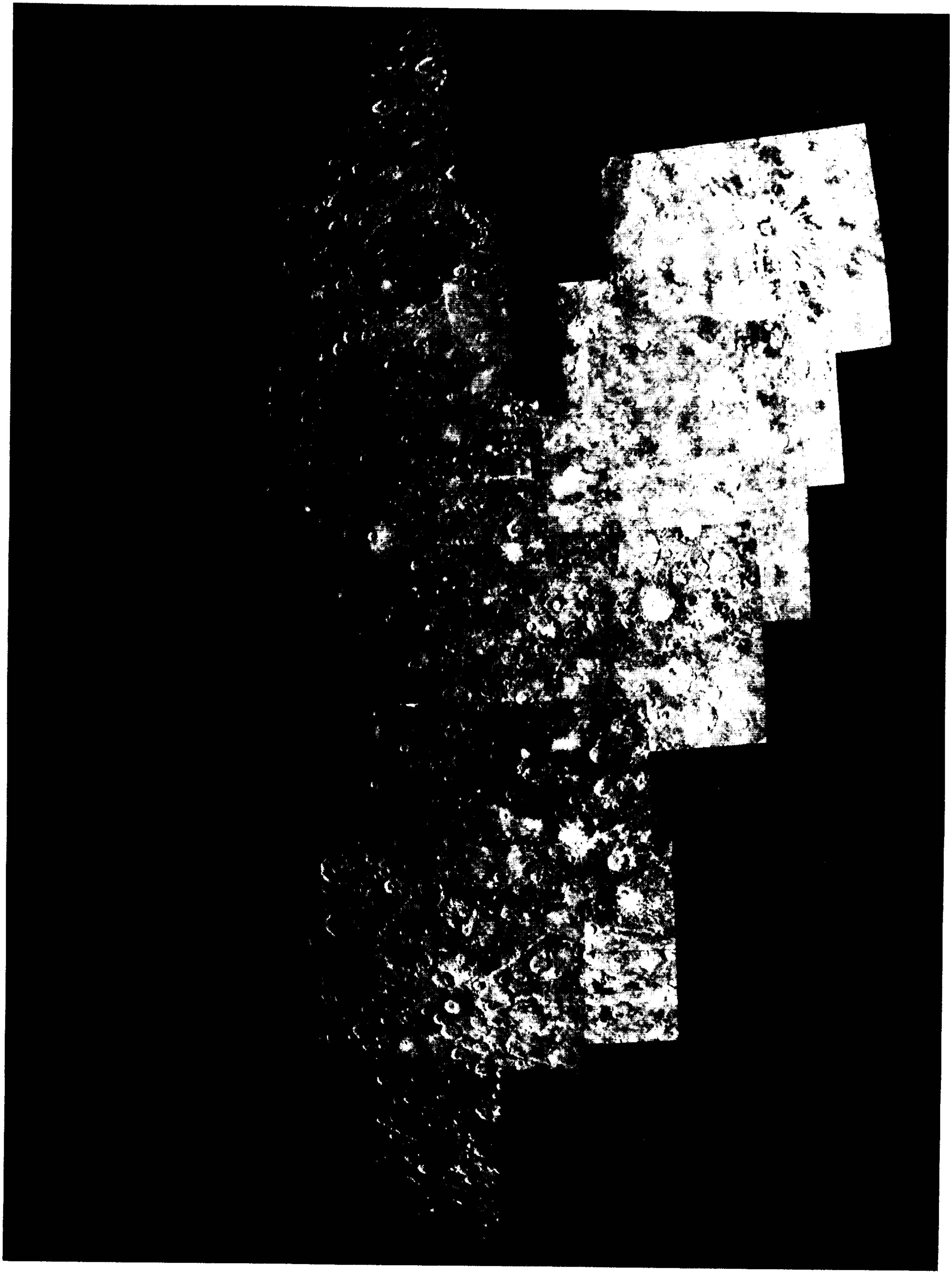


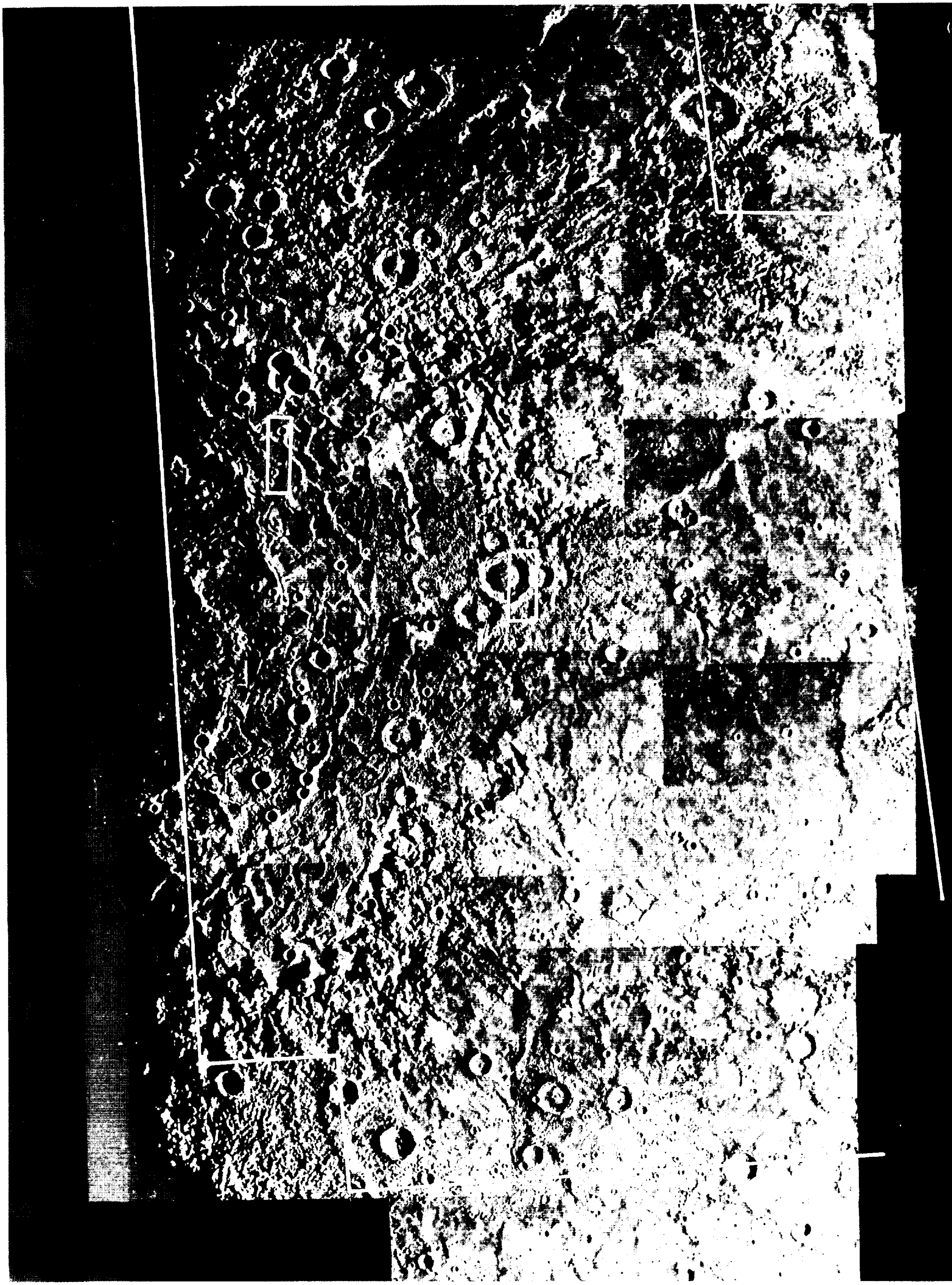
TIME FROM CLOSEST APPROACH
0 d 1 h 45 m 42 s

Fig. A-24. The final mosaic of the second encounter sweeps northward to include the Caloris Basin, seen from a somewhat different viewpoint compared with the first encounter.

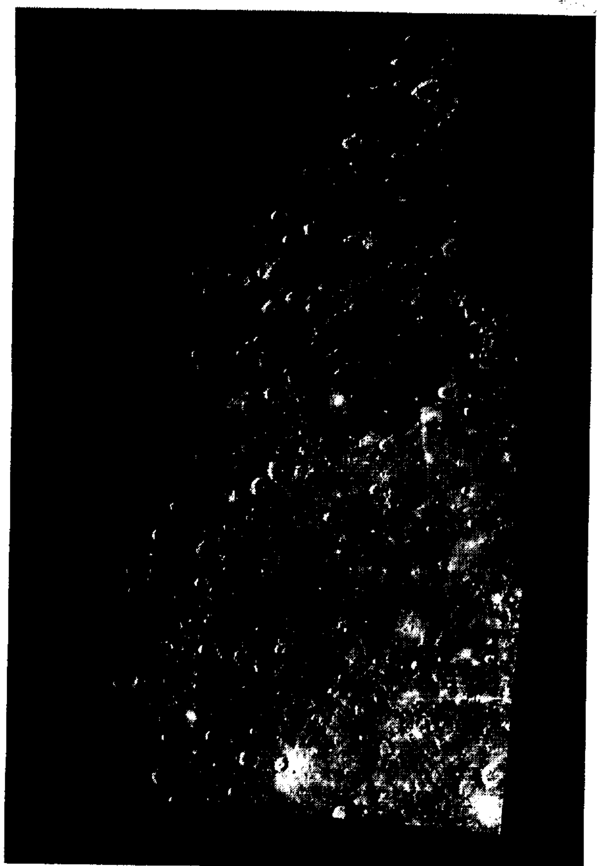


TIME FROM CLOSEST APPROACH
0 d 3 h 8 m 18 s





(a



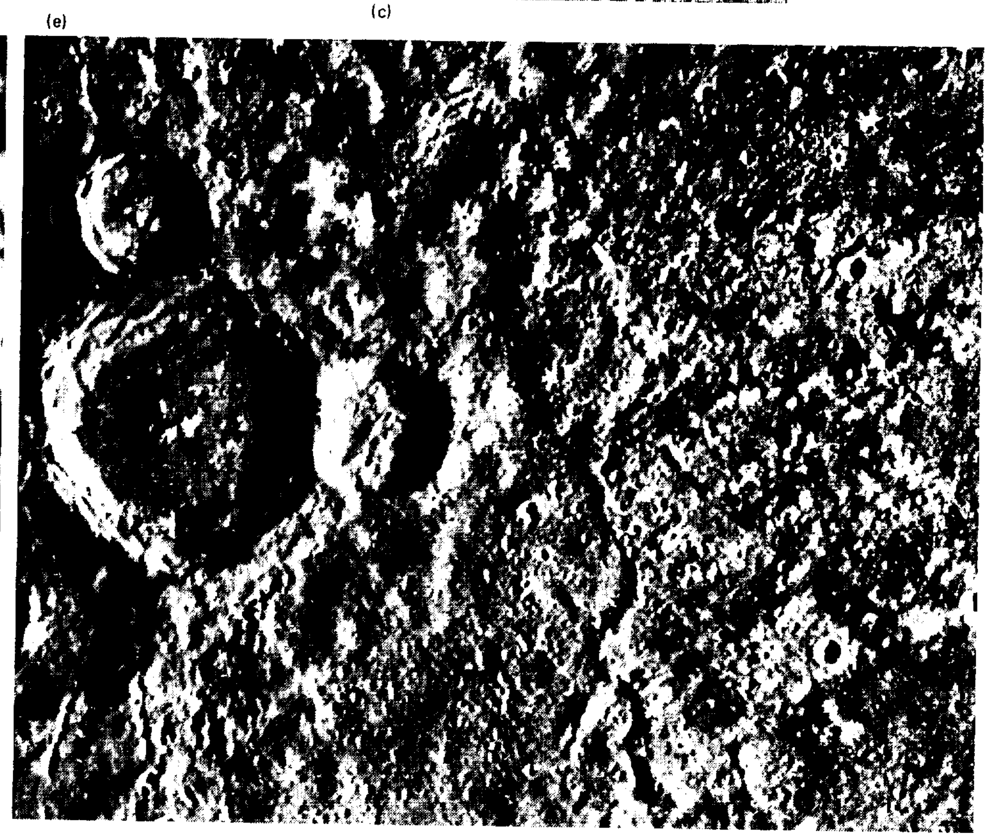
(b)

Fig. A-25. The Caloris Basin as imaged at the three encounters is shown in this series of photographs. In the computer-enhanced mosaic from Mercury I (a) is outlined the area viewed at Mercury II (b). The small white boxes identify the locations of the high-resolution frames (c) and (d) obtained at Mercury III. Alongside (d) is shown a high-resolution picture of the same crater—tentatively termed the "Teddy Bear"—taken at Mercury I (e).

(c)

(d)

(e)



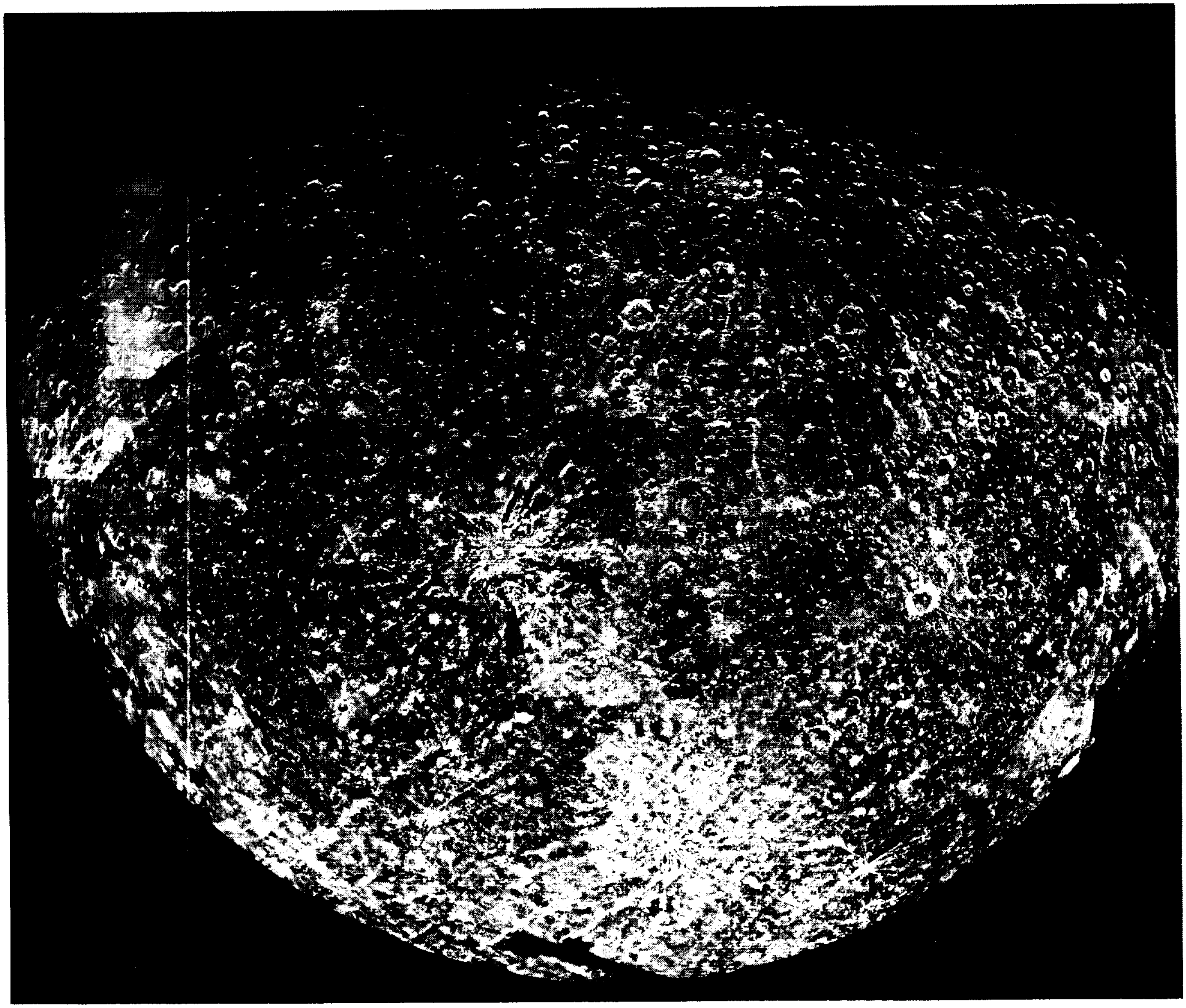
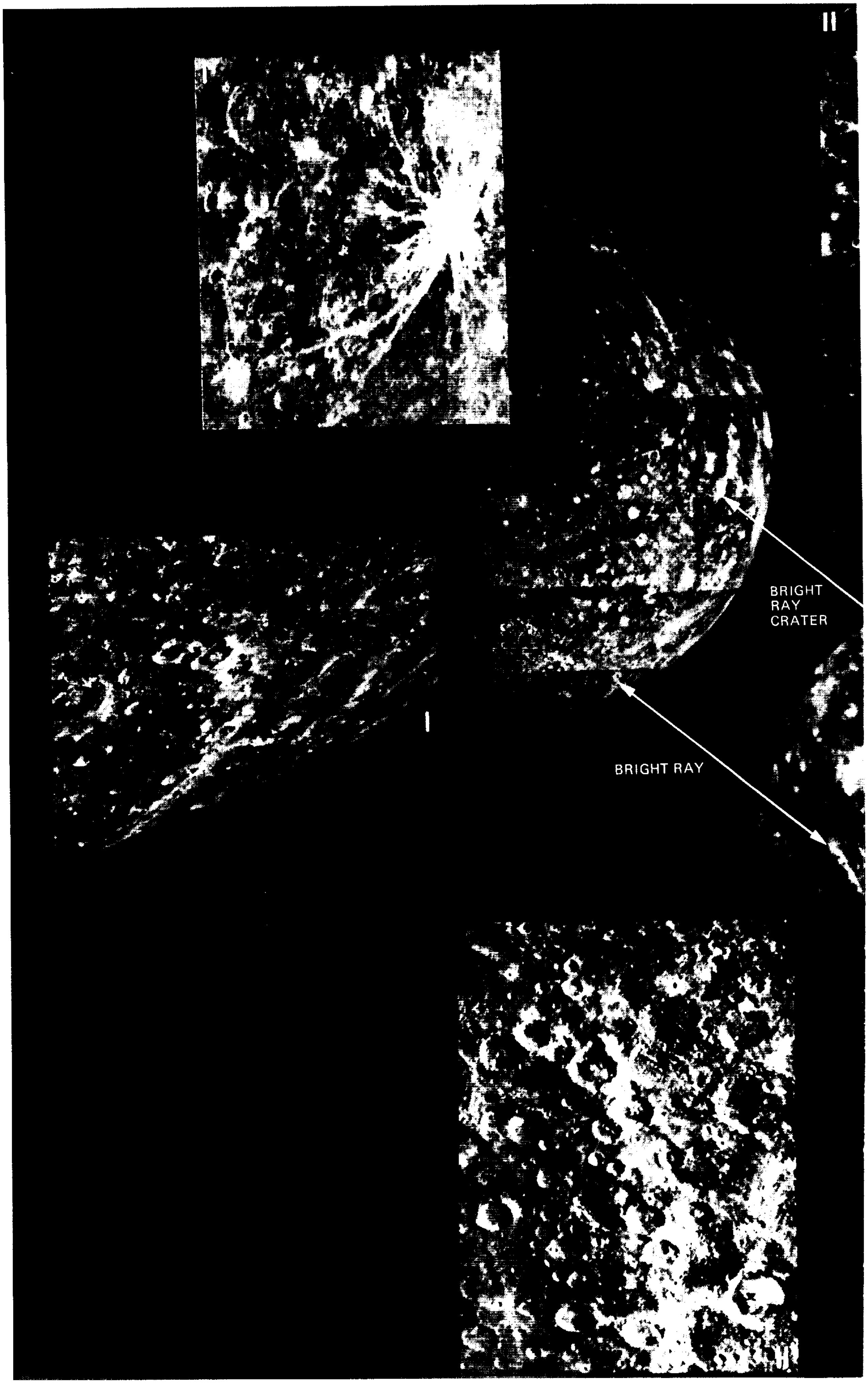
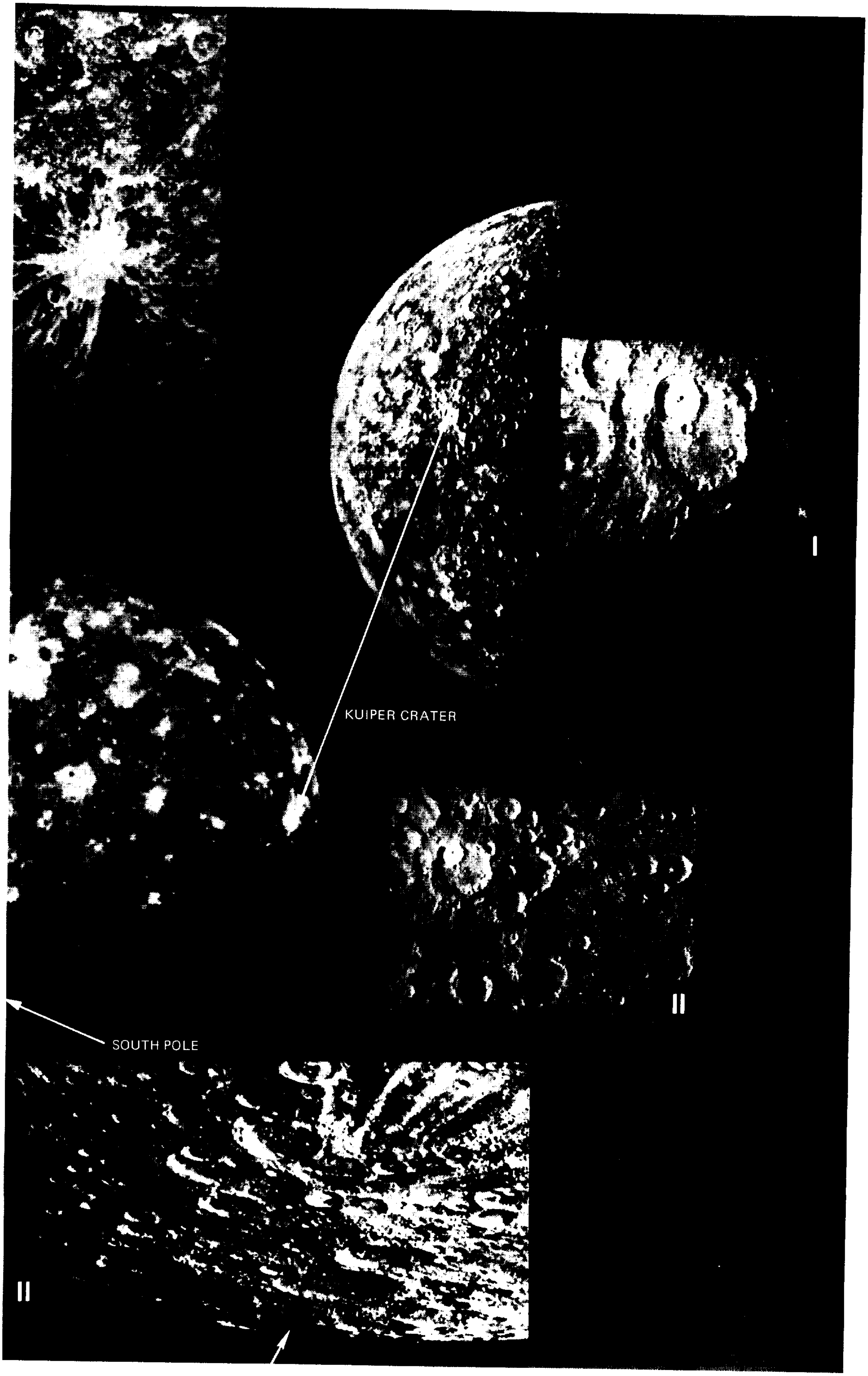


Fig. A-26. This unusual view of Mercury was prepared from hand assembly of individual pictures, computer-enhanced and projected for a viewpoint close to the south pole. The crater containing the south pole of Mercury is the large one in shadow on the terminator at the bottom of the mosaic. This view links many of the former mosaics.

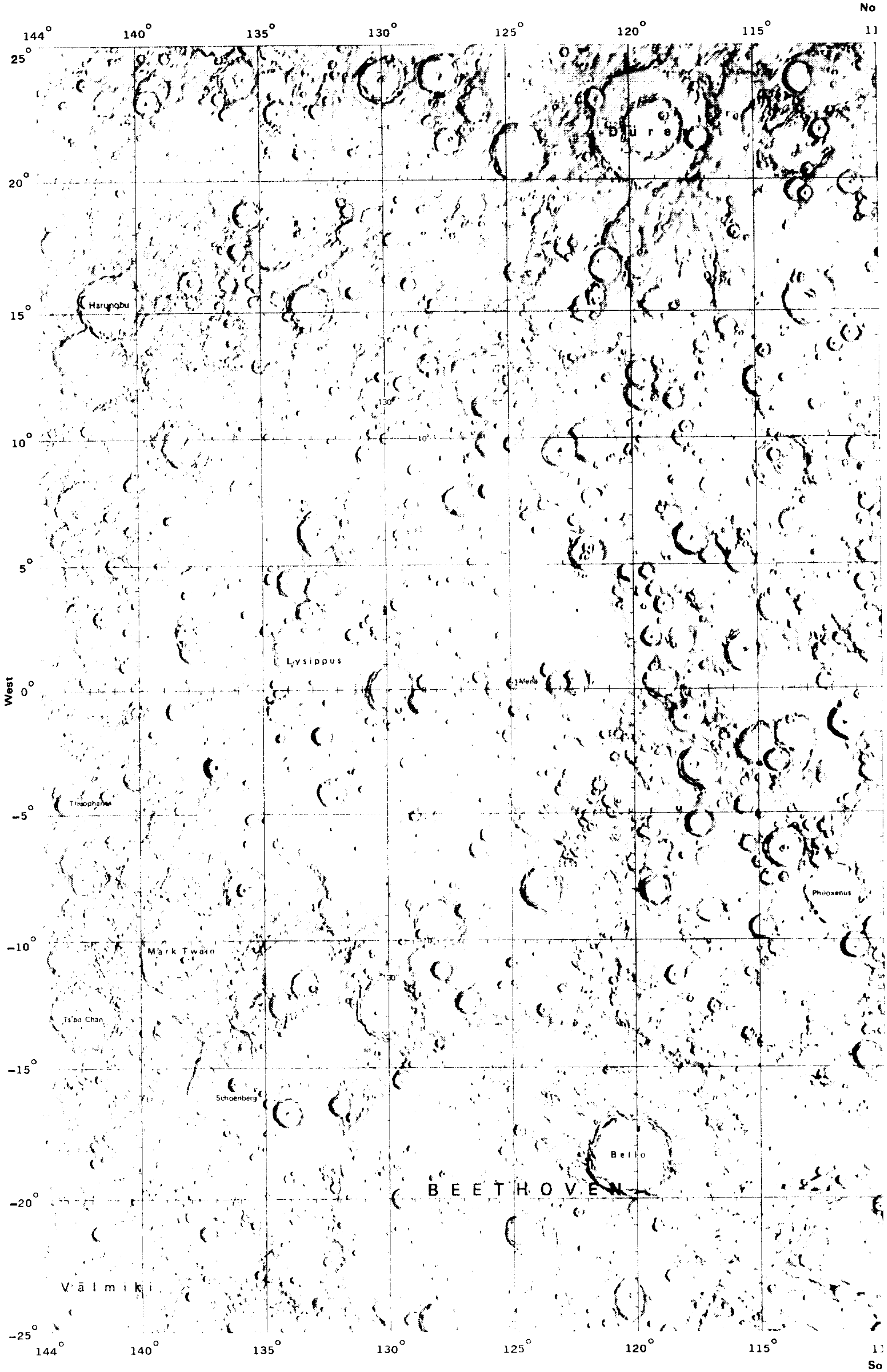
Fig. A-27. Shown on the following two pages are comparative views of the incoming and outgoing mosaics of Mercury I and a wide-angle polar view obtained during Mercury II presenting a view similar to Fig. A-26. Several features are identified on each mosaic and shown in high-resolution images alongside.



II
I
BRIGHT
RAY
CRATER
BRIGHT RAY



KUIPER CRATER
I
II
SOUTH POLE
II



No
144°
140°
135°
130°
125°
120°
115°
25°
20°
15°
10°
5°
0°
-5°
-10°
-15°
-20°
-25°
West
Dürer
Harunobu
Lysippus
Mena
Theophanes
Philoxenus
Mark Twain
Ts'ao Chan
Schoenberg
Bello
BEETHOVEN
Vālmiki
So

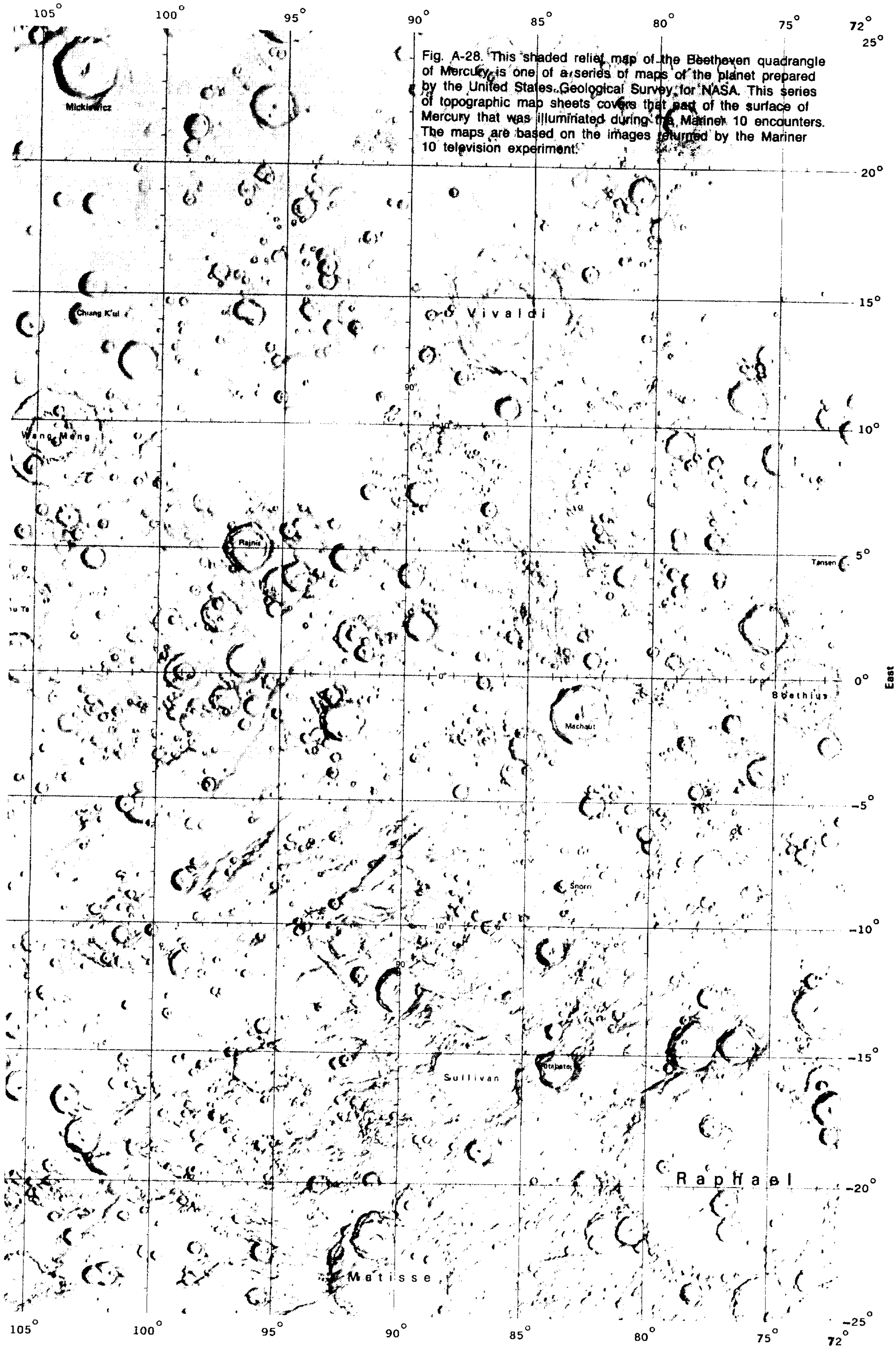
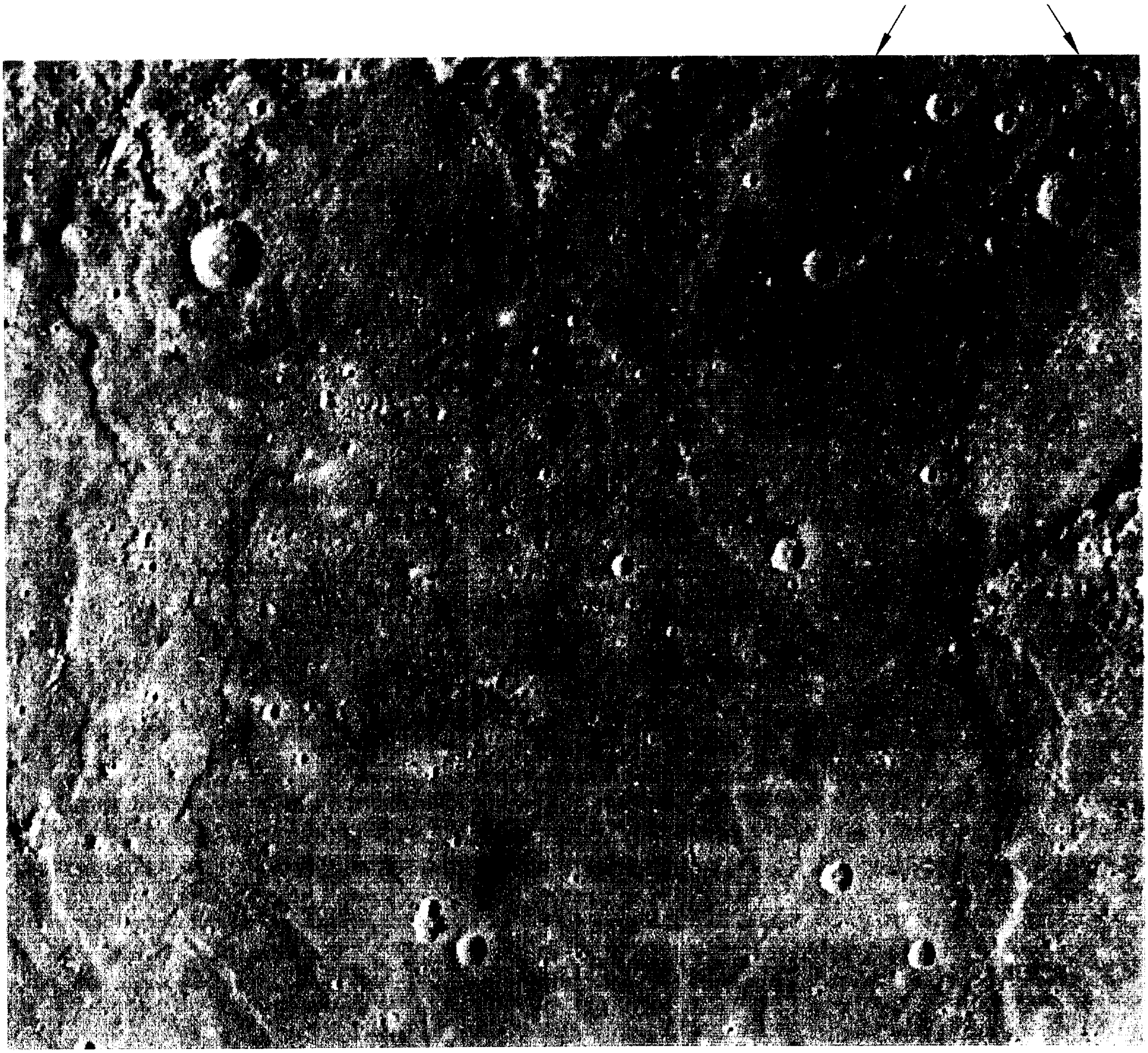
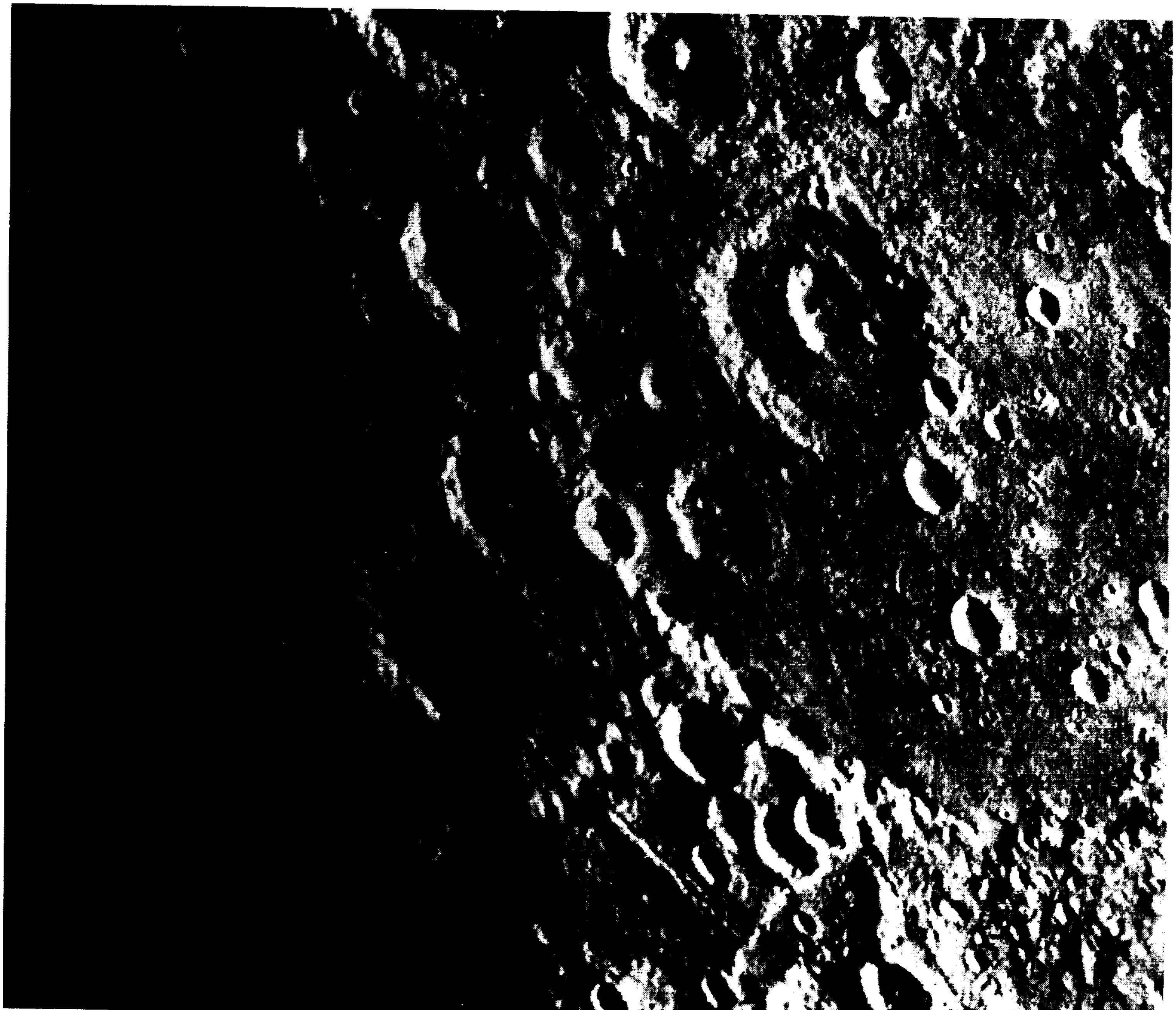


Fig. A-28. This shaded relief map of the Beethoven quadrangle of Mercury is one of a series of maps of the planet prepared by the United States Geological Survey for NASA. This series of topographic map sheets covers that part of the surface of Mercury that was illuminated during the Mariner 10 encounters. The maps are based on the images returned by the Mariner 10 television experiment.

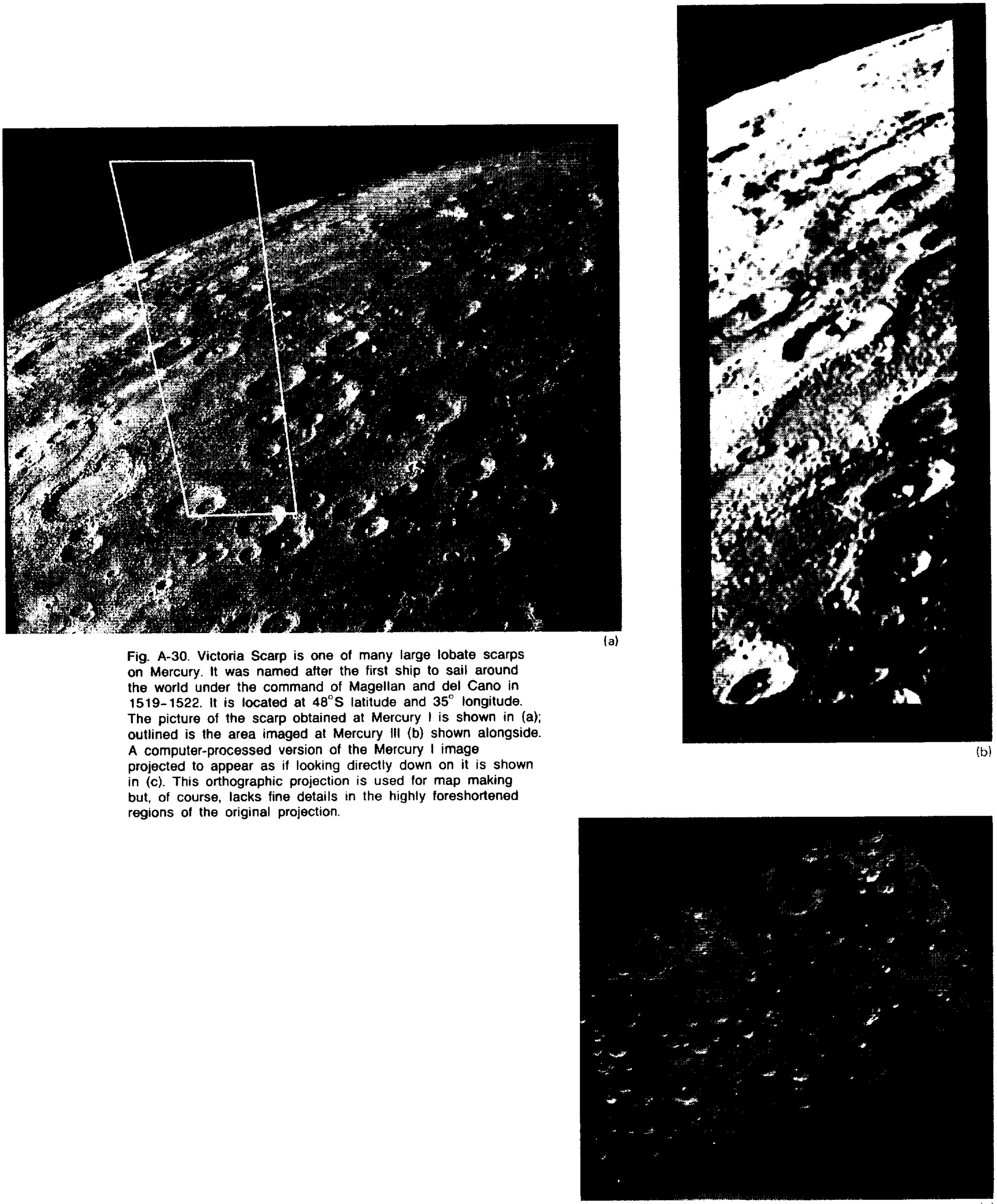


(a)

Fig. A-29. Close inspection of the many individual frames used to make the mosaics of the earlier figures provides a wealth of new information about the innermost planet. The presence of other large basins was confirmed. In (a) is shown a flooded 240-km (150-mi) diameter basin, its walls indicated by arrow heads, as revealed at Mercury I. Another flooded basin (b) photographed at Mercury II is 350 km (220 mi) in diameter and appears to be flooded with plains material and then subsequently cratered by some large impacts. Not only did the filling material partially inundate small craters which had formed along the rim of the basin at the lower left but also overflowed the rim and spilled onto the surrounding terrain at the top right.



(b)



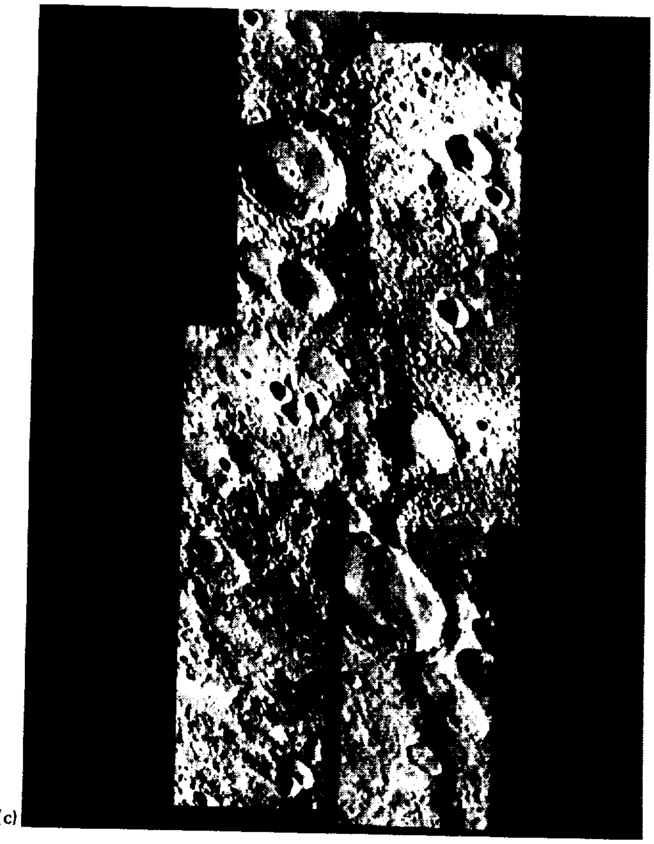
(a)

(b)

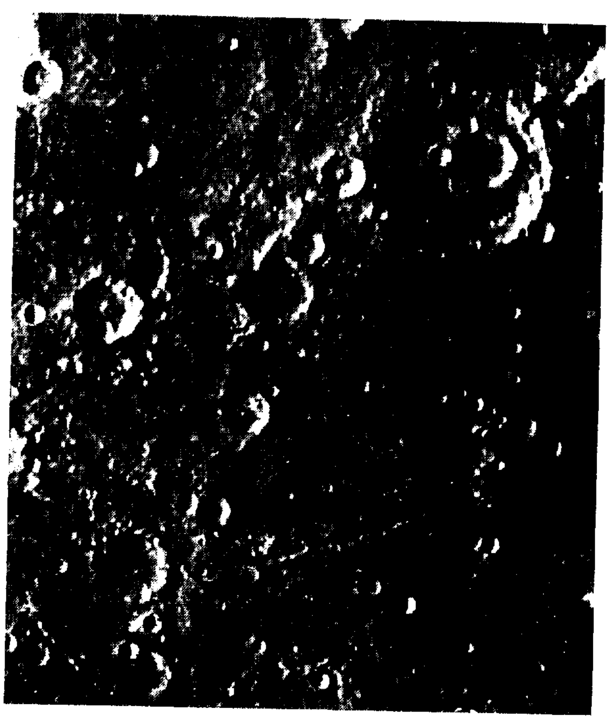
(c)

Fig. A-30. Victoria Scarp is one of many large lobate scarps on Mercury. It was named after the first ship to sail around the world under the command of Magellan and del Cano in 1519-1522. It is located at 48°S latitude and 35° longitude. The picture of the scarp obtained at Mercury I is shown in (a); outlined is the area imaged at Mercury III (b) shown alongside. A computer-processed version of the Mercury I image projected to appear as if looking directly down on it is shown in (c). This orthographic projection is used for map making but, of course, lacks fine details in the highly foreshortened regions of the original projection.

(a)

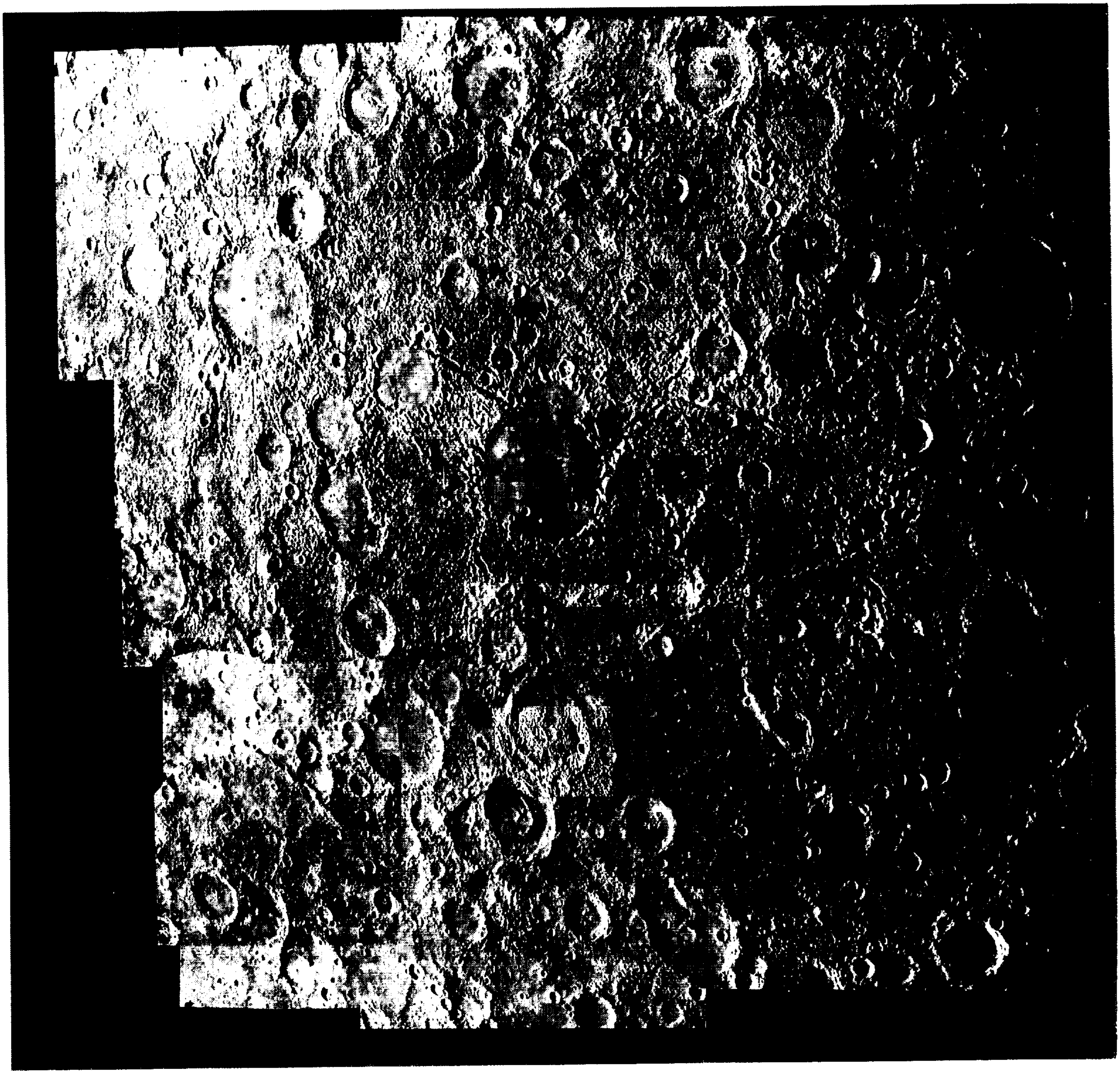


(c)

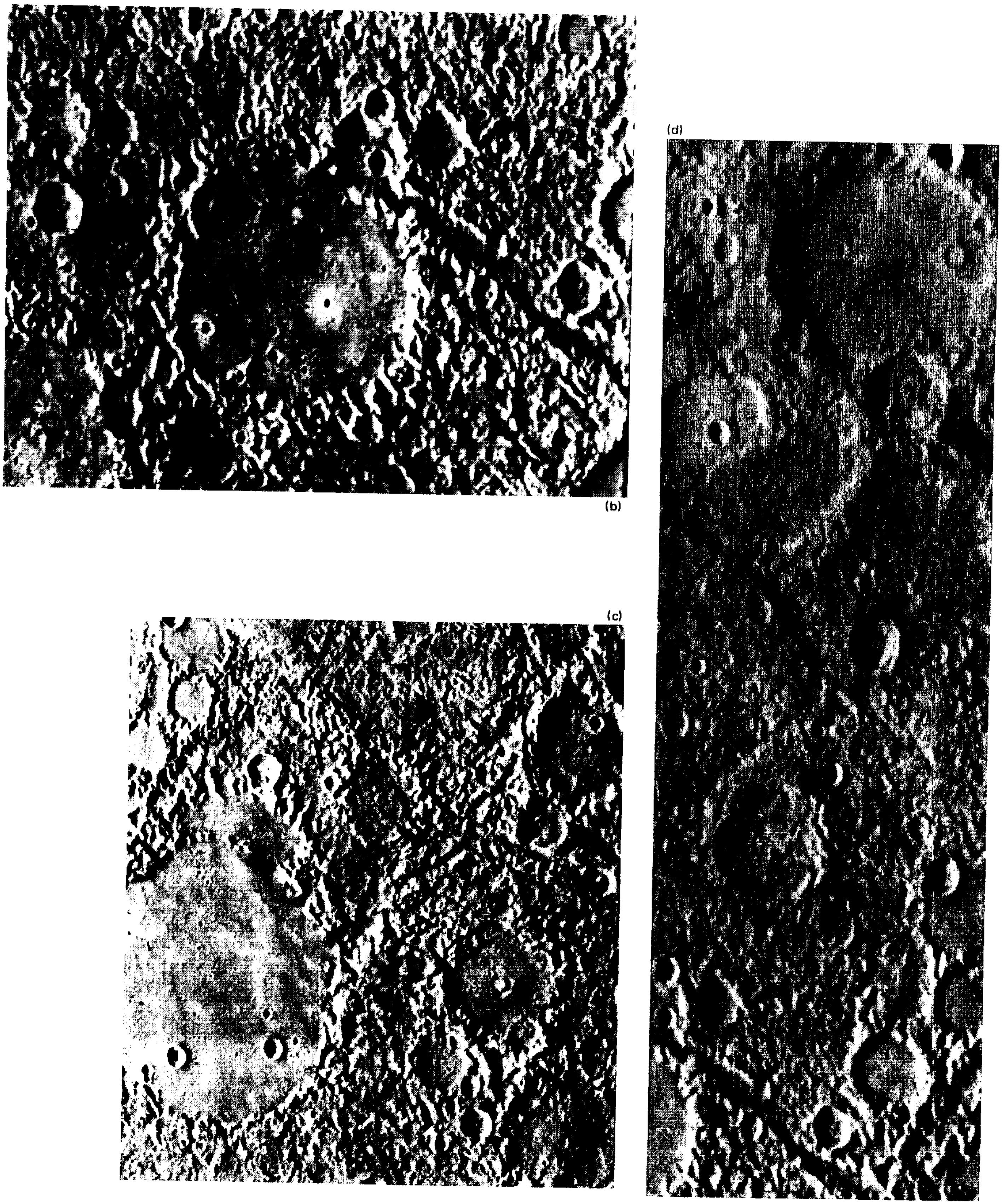


(b)

Fig. A-31. Discovery Scarp, at latitude 52°S and longitude 35°, was photographed at the first, second, and third encounters. A Mercury I picture (a) shows the scarp transecting craters on the right side of the picture. A smaller scarp runs through the floor of a large crater at the top and into surrounding terrain. This picture also shows two long, narrow valleys consisting of many small craters. Mercury II (b) shows the southern section of the scarp from a somewhat different viewing angle. The two transected craters are not included in this image. Mercury III (c) provides high-resolution detail of the northern section of the scarp and again shows the transected craters. The viewing angle is very similar to that of Mercury I. Note that in the larger crater there is a graben-type valley to the right of the scarp, but no such feature in the smaller of the transected craters.



(a)
Fig. A-32. The jumbled terrain antipodal to the Caloris Basin was also covered in detail by Mariner. A photomosaic from Mercury I (a) shows the peculiar nature of this area of hills and ridges cutting across craters and intercrater areas. The rims of flat-floored craters are partially disrupted and hills are dissected. A close view of part of this terrain is shown in (b) and an even closer view in (c). A high-resolution frame within the area obtained by Mercury III is shown in (d). Since this terrain is antipodal to the Caloris Basin, it has been speculated that it may have been caused by a focussing of seismic forces originating from the Caloris impact.



(b)

(c)

(d)

An Astronaut's View of Mercury

Three stereo pairs of photographs of Mercury are reproduced on the following six pages. Obtained at Mercury I and II, these photographs provide an astronaut's view of the surface of the innermost planet. The locations of the areas covered by stereo are shown on Fig. A-34 on the facing page.

The right picture of each pair has been reversed in printing so that the pairs can be viewed in stereo with a simple plane mirror as shown in Fig. A-33. Place the book opened flat on a table so that both pictures of a pair are illuminated brightly and equally, i.e., facing a window or a good desk light. Take a plane mirror (a 12- by 12-in. wall tile mirror from a hardware store is ideal) and place it vertically on the center of the book as shown in the figure, its reflecting surface to the right. Look directly down on the book as shown in the photograph, placing the nose on the top edge of the mirror. Look at the left-hand picture with the left eye and slightly rotate the head so that you look at the reflection of the right hand picture with the right eye, both eyes looking toward the left-hand picture because of the tilt of the head. The right eye reflected image is now superimposed over the left eye direct image. This superimposition is aided if you close first one eye and then the other alternatively and concentrate on tilting the head and the mirror very slightly so that the right-hand and left-hand images of one of the prominent craters concide.

The view of Mercury pops out in sharp relief; you gain the impression of height as though you were an astronaut flying over the surface of the innermost planet.

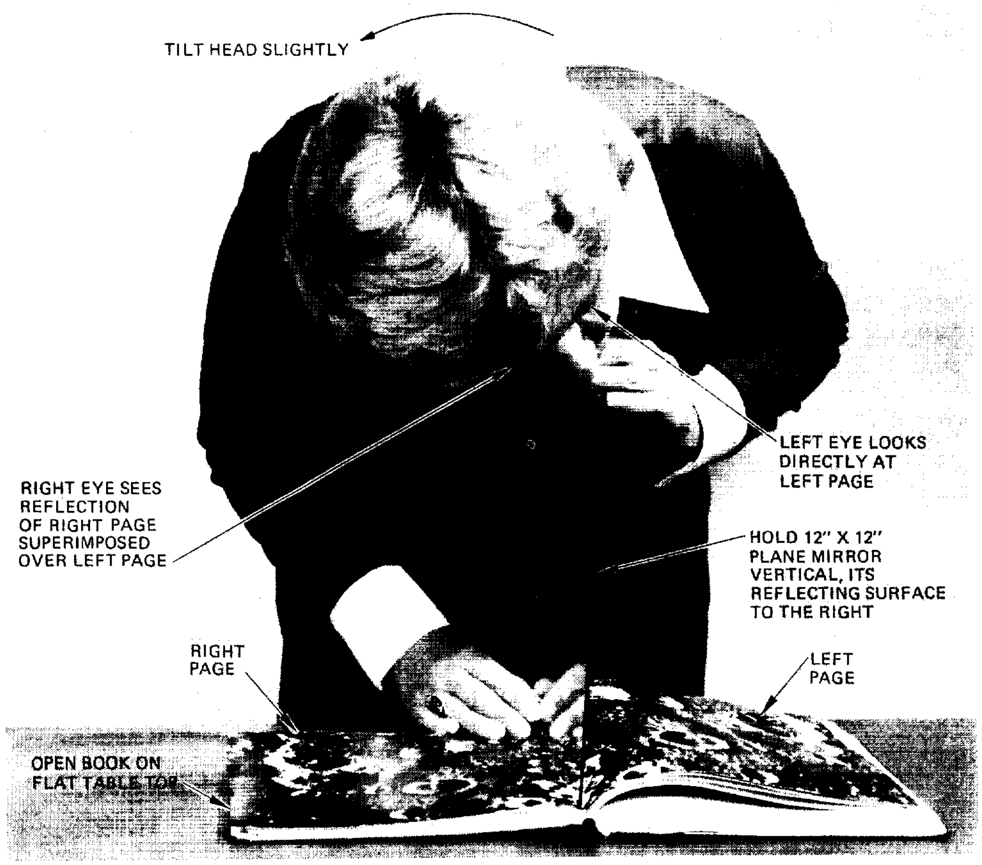
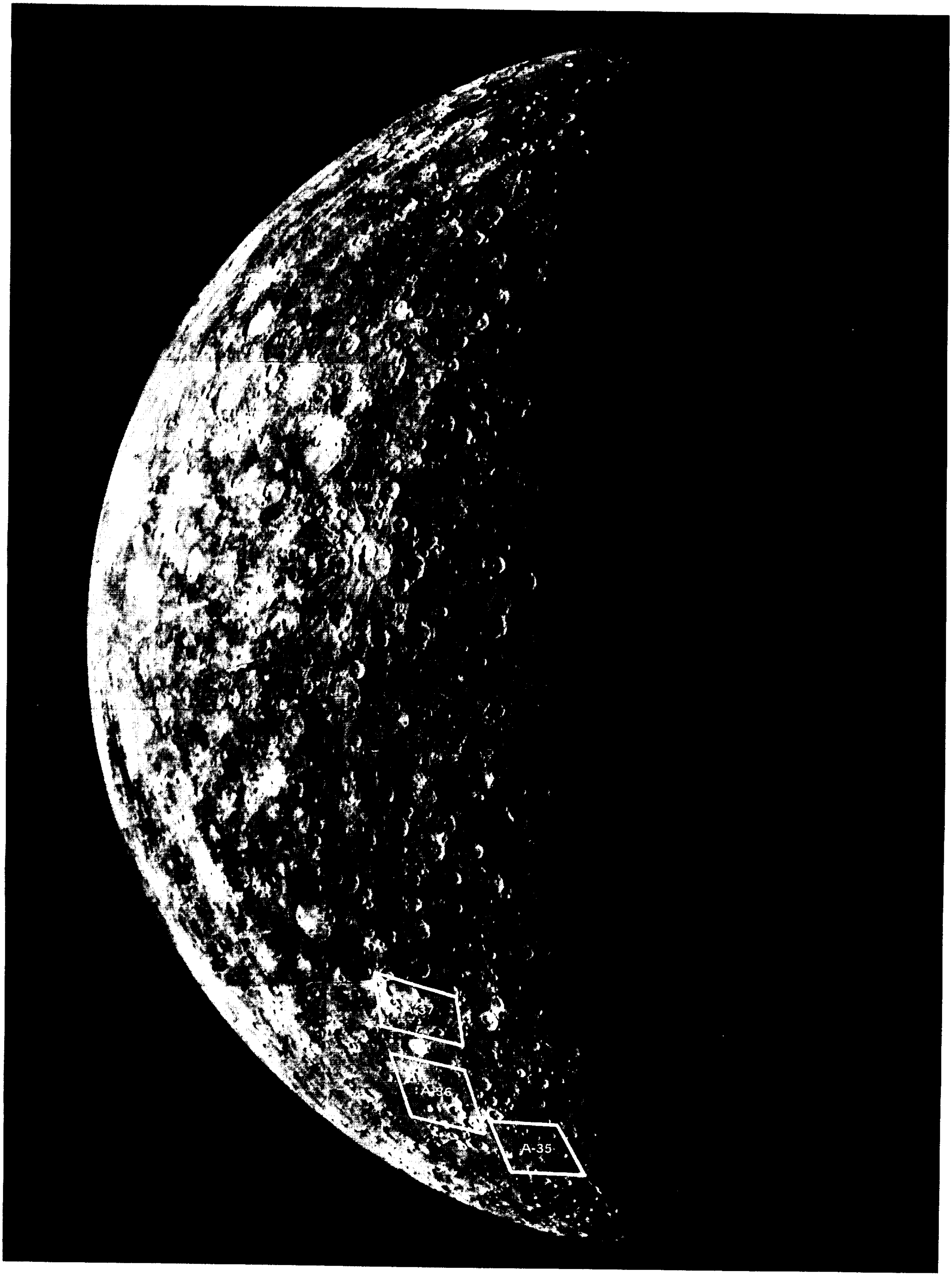
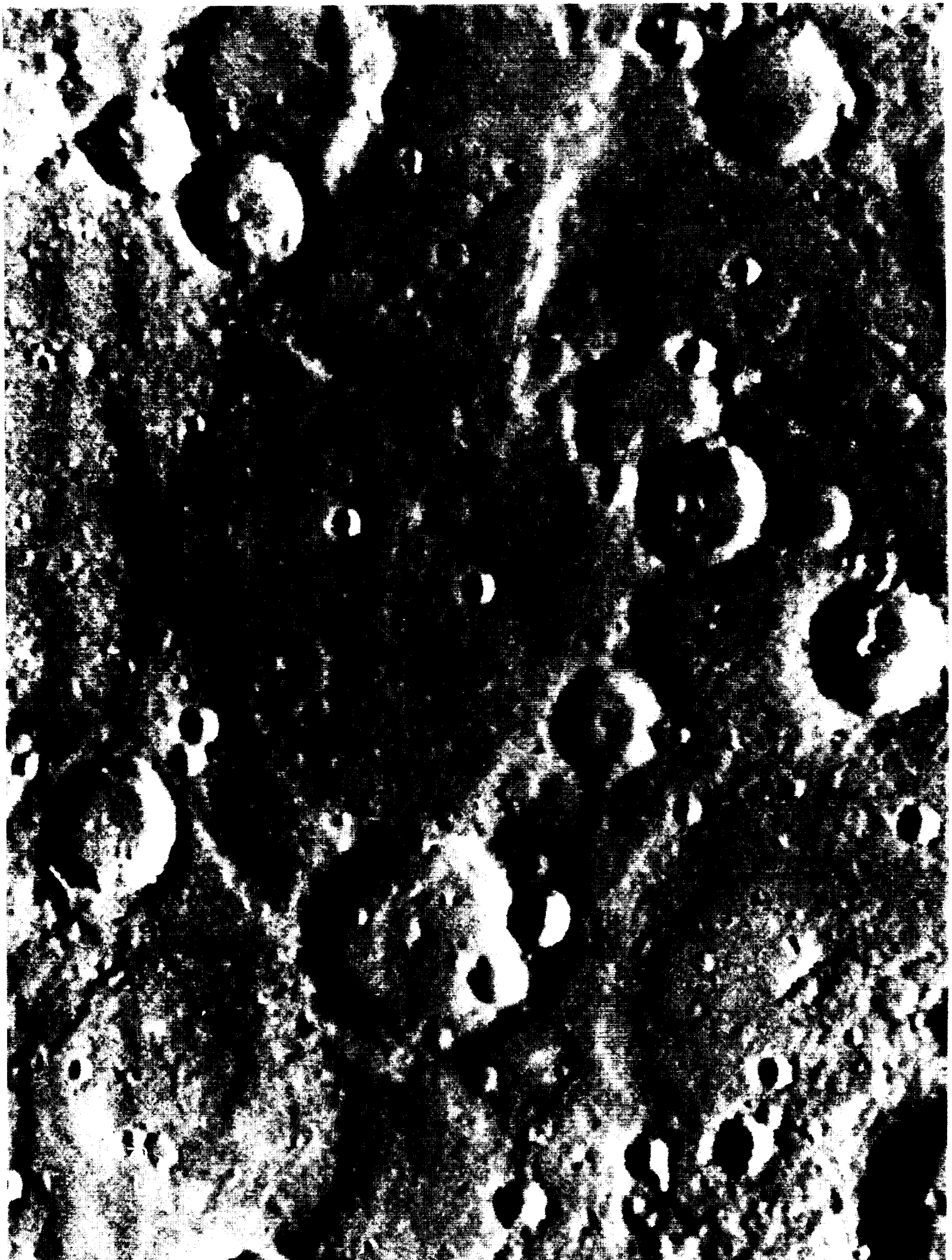


Fig. A-33. How to view the stereo pairs with a 12- by 12-in. wall tile mirror.

Fig. A-34. Locations of the stereo pair areas on the incoming mosaic of Mercury.



A-37
A-36
A-35



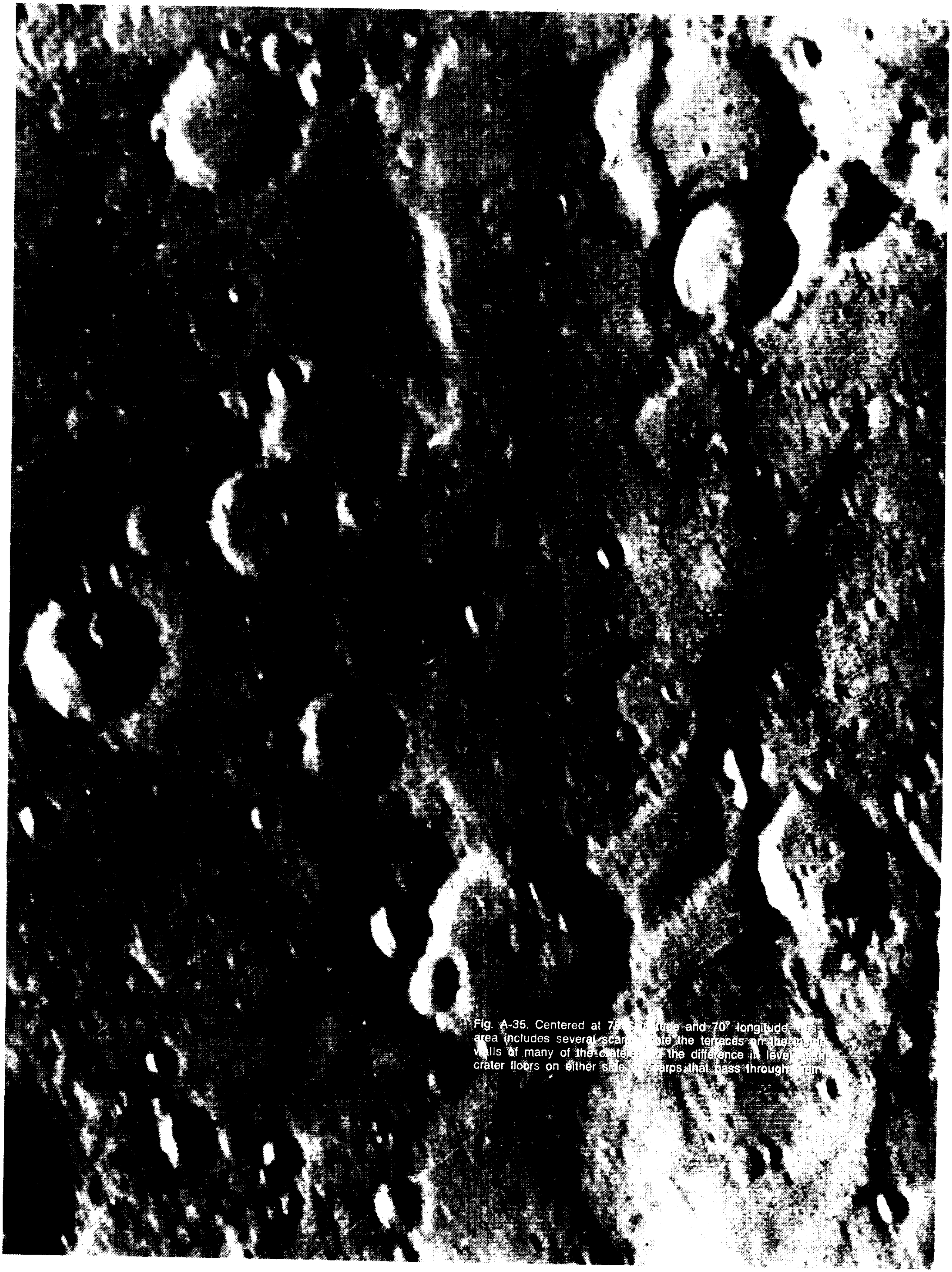
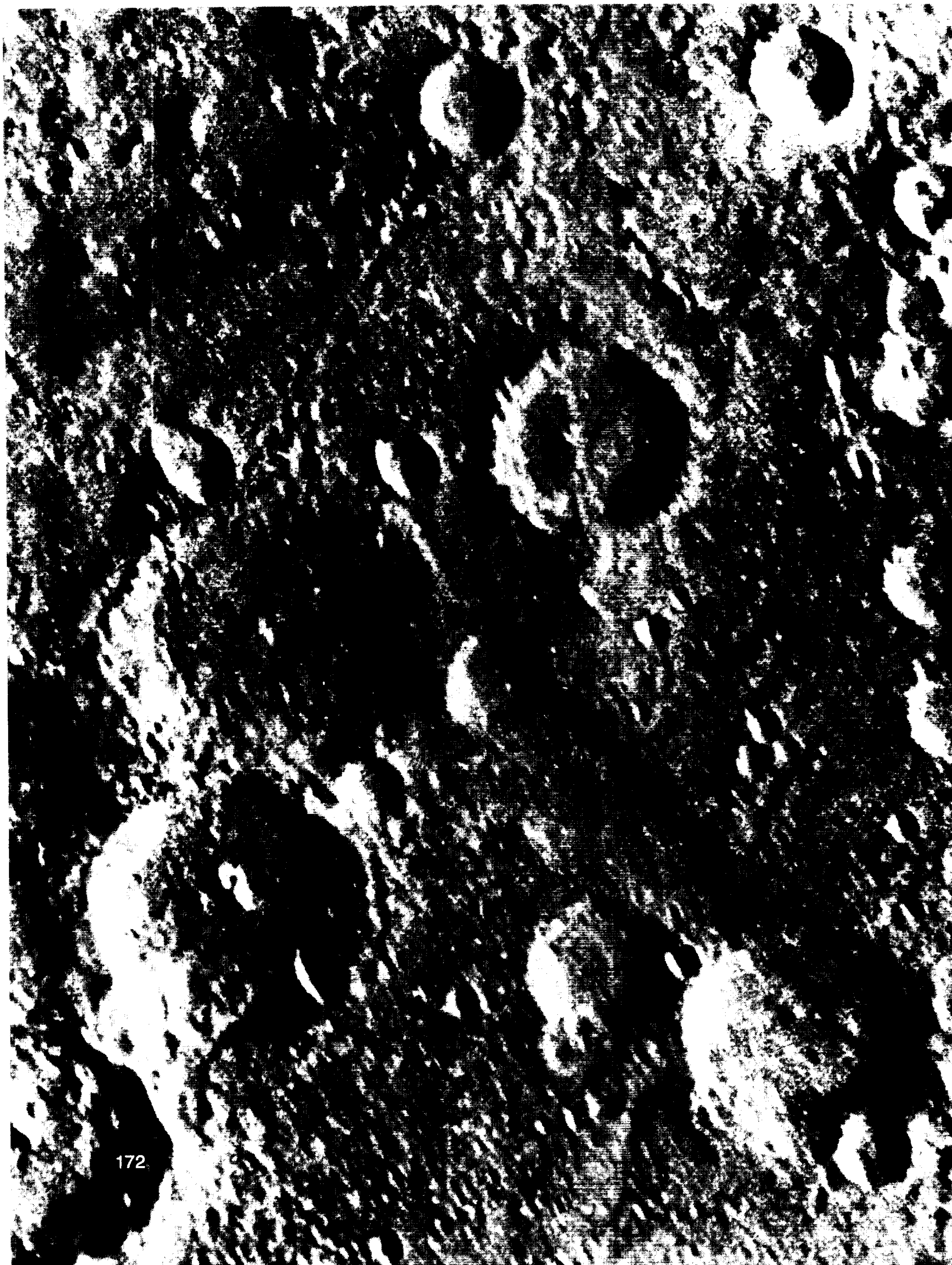
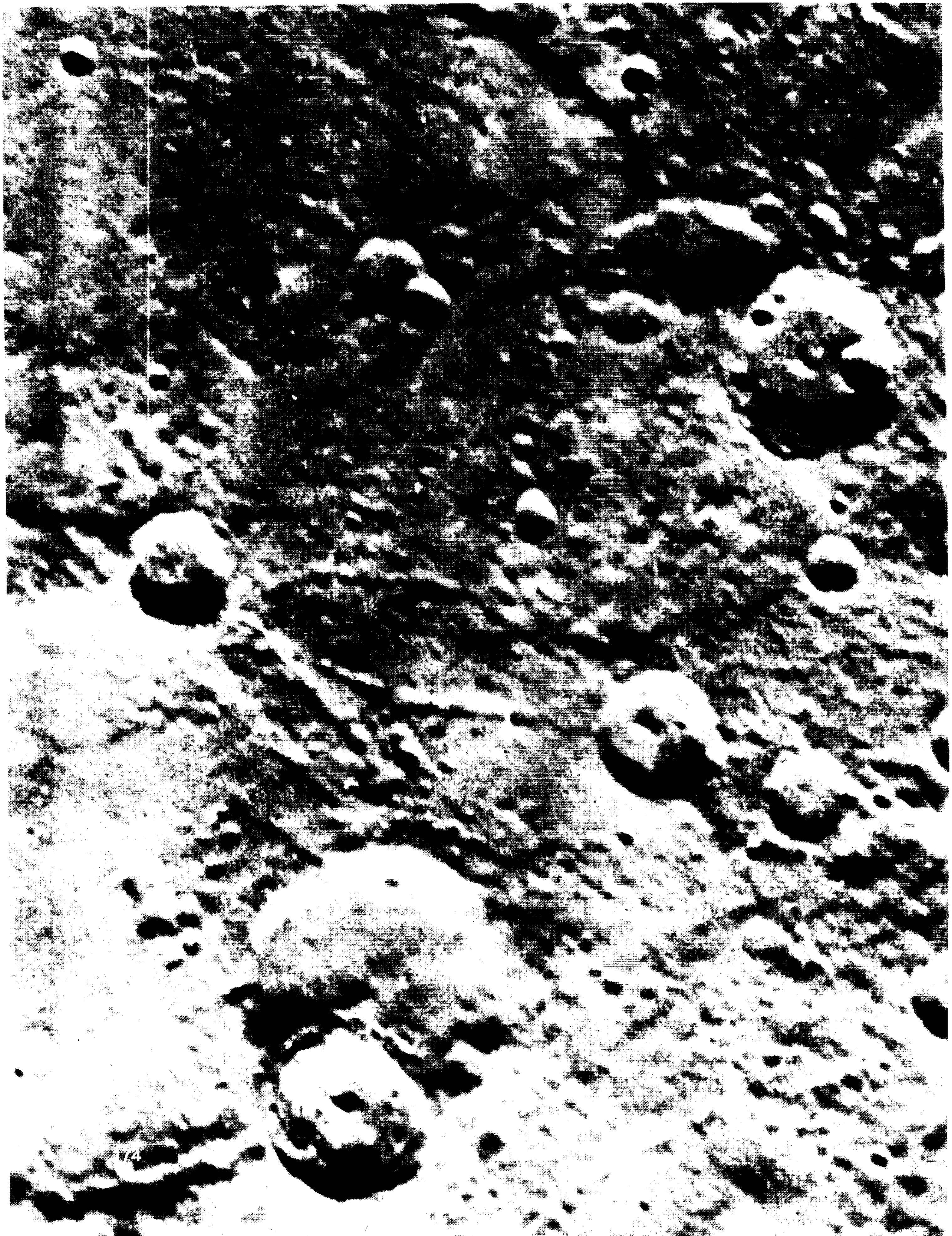


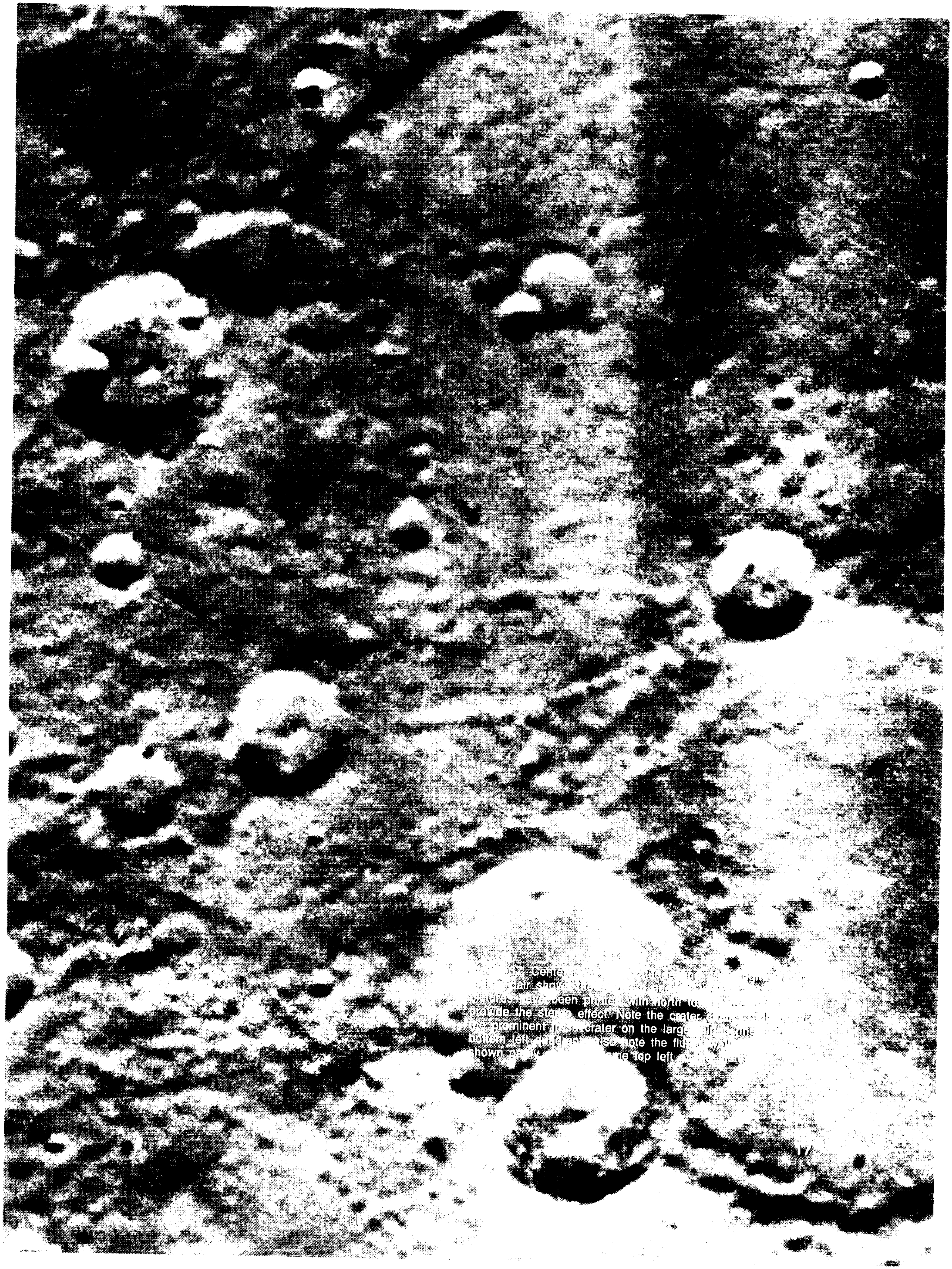
Fig. A-35. Centered at 75° S latitude and 70° longitude, this area includes several scarps. Note the terraces on the inside walls of many of the craters and the difference in level of the crater floors on either side of scarps that pass through them.



172

Fig. A-36. Centered at 64°S latitude and 64° longitude, this area shows another prominent but as yet unnamed scarp. Note how it passes through the floor of the large terraced crater at the bottom left, showing that the crater was formed before the scarp.





[illegible] Cente[illegible] pair show [illegible] been printed with north [illegible] provide the ste[illegible] effect. Note the crater [illegible] the prominent [illegible] crater on the larg[illegible] bottom left [illegible] also note the flu[illegible] shown [illegible] the top left [illegible]

Appendix B
Processing the TV Images

Data returned from the spacecraft are recorded on the ground in what are termed data records. The original data record (ODR) is a local-computer-processed record on magnetic tape of the data as received at the ground station. This record can be replayed from the station only after the pass has been completed, i.e., when the station has ended its communication with the spacecraft.

A system data record (SDR) is made at the Mission Control and Computing Center from the data transmitted in real-time by the receiving stations over ground data links to the Jet Propulsion Laboratory. This record always contains more errors than the original data record; but whereas the original data record takes time to transport physically to Pasadena, the systems data record is available in real-time. The production of these records is shown in Fig. B-1. Also shown on the figure is an analog record made at each Deep Space Network station, recording the received signals in their raw form before any computer processing takes place.

An experimenter data record (EDR) was later produced from a merging of the original and systems data records to eliminate some erroneous data. From this experimenter data record the science data were supplied to experimenters, including the television experimenters.

The experimenter data record tapes were physically transferred to the Video Analysis Facility at the Laboratory, where a library of tapes is maintained. These tapes can be processed into photographic copies in the Image Processing Laboratory on a variety of machines that convert the digital information on the tapes into small gray squares (pixels) on a photoemulsion. These squares of different shades of gray, arranged side by side in adjacent lines, build up the complete picture, just as photographs reproduced in a newspaper are built up of many small black dots of different sizes. Because there are sufficient numbers of these pixels, the shades of gray of each pixel are fused by the eye into a continuous, smooth-looking picture (Fig. B-2).

As each picture became available from Mercury or Venus it was displayed in a raw version on screens in the Mission Command and Control Center. Because of the high data rate associated with real-time transmission of the pictures, every picture could not be displayed in real-time. However, those that were shown enabled the experimenters to gain a good idea of the quality of the imaging and to make sure that the imaging sequence was proceeding according to the plan laid down before the encounter.

A Digifax system allowed close-to-real-time (30-min delay) production of hard-copy pictures of the TV images that were displayed on the real-time screens. An improved photoimage of each TV frame was available some time later through the mission test computer. This was known as the MTC version of each picture. Later still there was an even more refined version available, known as the IPL, since it was produced by the Image Processing Laboratory. Figure B-3 compares these three versions of a single picture of Mercury.

The MTC photoimages were sent in raw and filtered versions of enhanced detail to the National Space Data Center at NASA-Goddard Space Flight Center, where scientists worldwide can obtain access to them. 70-mm versions of all pictures on film were also sent to the Science Data Center.

The most sophisticated pictures result from the operations of the Image Processing Laboratory. Here the analysts can change contrasts, rectify images, correct bit errors and accentuate details into the terminator regions. Figure B-4 shows an A-camera Mariner 10 image of Mercury as produced from the experimenter data record at the Image Processing Laboratory compared with the same image that has been corrected in the Laboratory by use of what is termed a convolutional filter to compensate for modulation characteristics in the electronics of the A-camera of the spacecraft. This considerably sharpened the features shown on the image. Figure B-5 shows a similar pair of pictures processed in this way for a B-camera image. Note particularly the increased fine detail in the floor of the large crater.

Figure B-6 illustrates how the Image Processing Laboratory can clean up errors in real-time pictures. The first picture (a) shows a Mercury I encounter picture as received at Canberra in real-time with a bit error rate of one error in 33 bits of data. This same picture is shown (b) after the computer at the Image Processing Laboratory detected and replaced 57,000 pixels that were in error. It did this by averaging between the correct neighboring pixels that surrounded each pixel in error. However, out-of-tolerance departures were processed differently. One of the five most significant bits was reset to bring the pixel value closest to the neighbor averages. This is a "smart" despiker algorithm in that it does not simply replace an erroneous pixel with neighbor averages.

The next two pictures, (c) and (d), show the same camera frame as received in real-time at Goldstone with an even greater error rate of 1 bit in 14, and as corrected by the removal and replacement of 128,000 pixels. Because of the higher error rate, the quality is not as good as the corrected picture from the Canberra station. Finally, a virtually error-free version of the picture that was recorded on the tape recorder of the spacecraft and later played back at a slow data rate is shown for comparison (e). While this picture is obviously much better than the high error rate but corrected image from Goldstone, it is not noticeably different from the corrected lower error rate Canberra picture. Indeed, a great deal of work went into a hard examination of the maximum allowable bit error rate so as to be able to use 117.6 kbits—the previous Mariner video threshold was 5 kbits only.

The next series of pictures (Fig. B-7) shows examples of another process of image improvement used by the Image Processing Laboratory. The Mercury I real-time image of Mercury as received by Canberra (a) has typical pixel errors, shown as dark spots all over the picture. The picture was processed (b) to remove these errors and also to correct for some photometric distortion in the spacecraft camera. Next (c) a two-dimensional, high-pass filter was used to retain 25% of the low-frequency brightness components, and the resultant image had its contrast increased about 2 times. Visually, the picture is more pleasing than the previous pictures and allows a better interpretation of the surface features.

The picture was then further enhanced (d) by correction of the characteristics of the camera in regard to the modulations obtained in its electronic circuits. Finally, because the spacecraft was looking at the planet at an angle, and the individual picture frames have to be assembled into large-scale mosaics of the planet's surface, the projection of the picture has to be changed. This, too, is done by the Image Processing Laboratory. The final picture in the series (e) shows the result of orthographic projection correction to the image frame.

On an airless planet such as Mercury, the amount of light reflected from the surface close to the terminator boundary between light and darkness is very much less than from the rest of the visible disc. Thus details of the images in the terminator regions are difficult to see. When a mosaic is made up of frames that are processed with normal contrast through a conventional high-pass filter, there is relatively poor contrast near the terminator, as illustrated in this Mercury I picture of the Caloris Basin (Fig. B-8). By putting these TV images through a spatially dependent filtering operation on the computer, the contrast and visibility of the features near the terminator is considerably improved (Fig. B-9).

The Image Processing Laboratory can also operate on pictures of a cloud-covered planet such as Venus to enhance the details of cloud structure. The series of images in Fig. B-10 show first the uncorrected raw image of Venus (a) followed by an image on which the spatial variation and nonlinearity in response of the spacecraft camera have been removed (b). The contrast was also increased 1.5 times on this photograph. Next (c) the contrast was increased still further to 3.5, making additional features of the clouds stand out. Then a two-dimensional, high-pass filter was applied to the pixels for about half of the planet, thereby removing global shading and making a more even illumination (d). The contrast on this image was increased 4 times. The next image (e) shows an even further increase in contrast to 8 times. Finally, a smaller high-pass filter was applied to emphasize the details of small-scale clouds in the atmosphere at two contrasts (f) and (g).

For Mariner 10 pictures to be used in mapping Mercury, the precise locations of craters and other objects are needed. The coordinates of control points for cartography are measured by counting pixels on versions of the photographs made especially for this purpose. Before launch, the coordinates of 111 positions on the vidicon tube of each camera were measured to high precision. Reseau marks appear on each image to relate it to the vidicon tube coordinates. A computer control program allows the pixel measurements of control points on an image frame to be related to image coordinates at the vidicon faceplate at the time the picture was taken. Since the position of the spacecraft relative to the planet is known at this same time, the precise location of the control points on the surface of Mercury can be determined relative to a latitude and longitude system on the planet.

To aid in counting pixels, some photographs are reproduced (Fig. B-11) with an orthogonal-type grid. Black and white dashes show every 25 pixels. Pixel measurements can be made to within one-tenth of a pixel, and by averaging the count of several people of the same control point, a suitably accurate measurement is obtained.

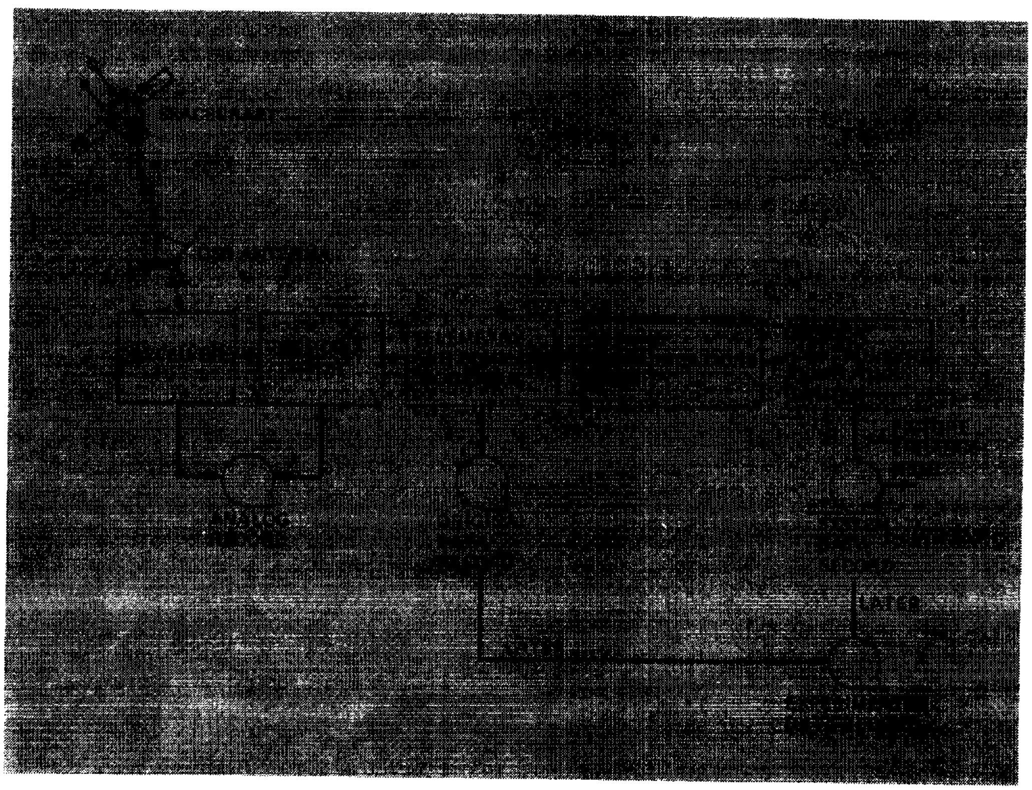
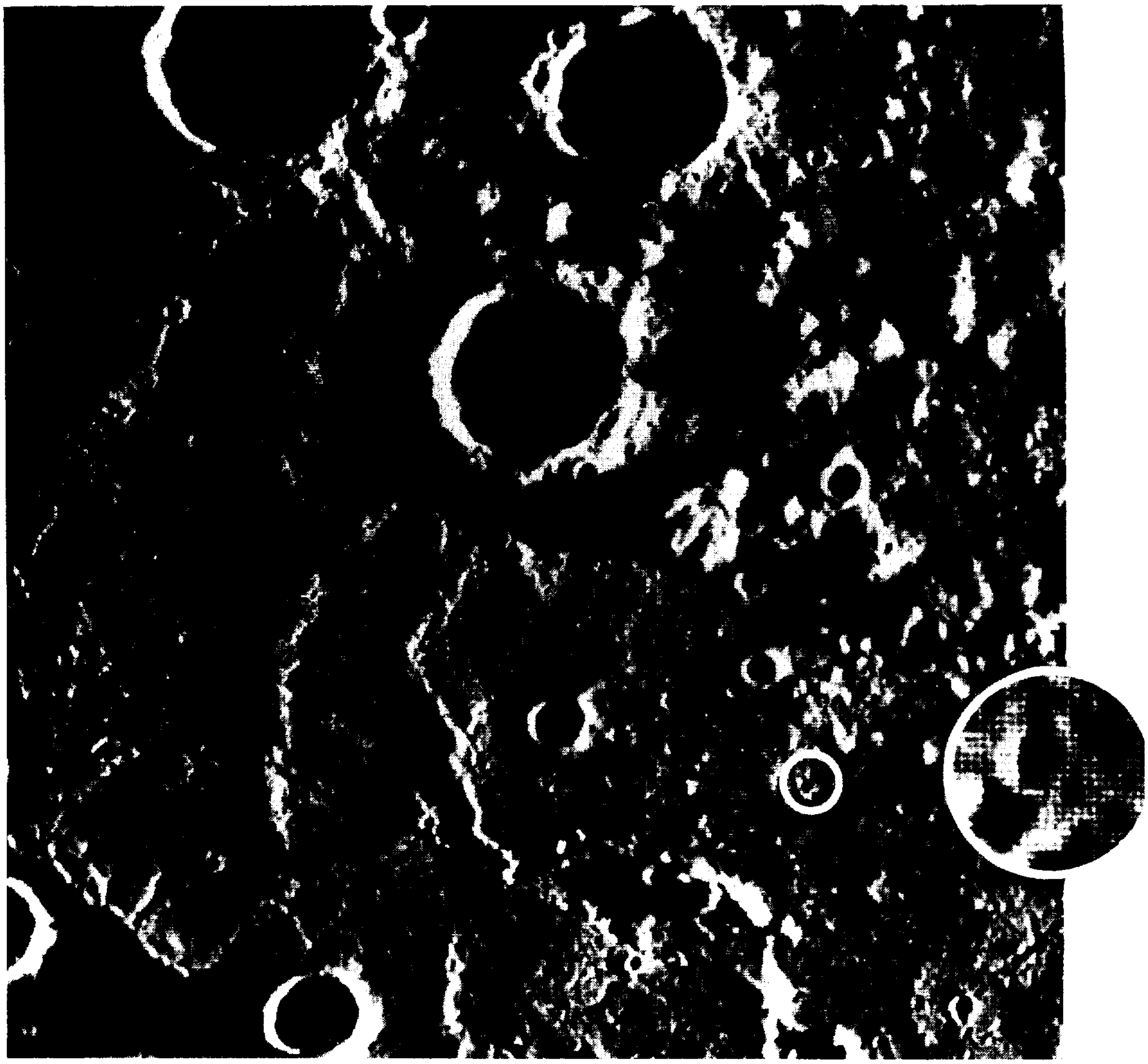


Fig. B-1. Several types of data records were produced for the Mariner Venus/Mercury mission.

Fig. B-2. The small area circled on the picture of Mercury (Caloris Basin) is enlarged to show the individual picture elements (pixels) that make up the picture. Each of these elements is transmitted from the spacecraft as a binary number which the ground computer processes through phototerminals into the reconstructed picture to duplicate the picture originally recorded on the vidicon aboard the spacecraft.



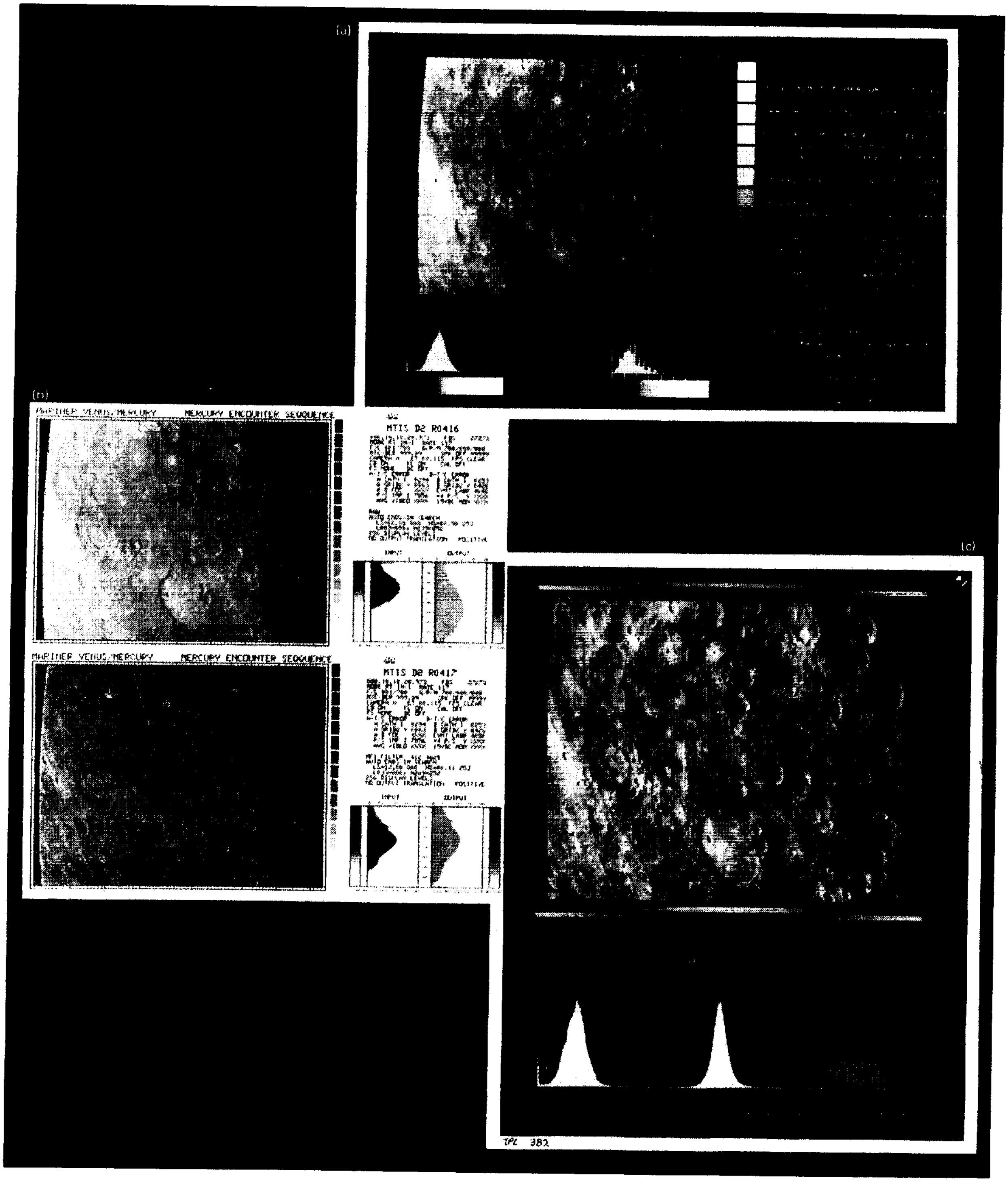
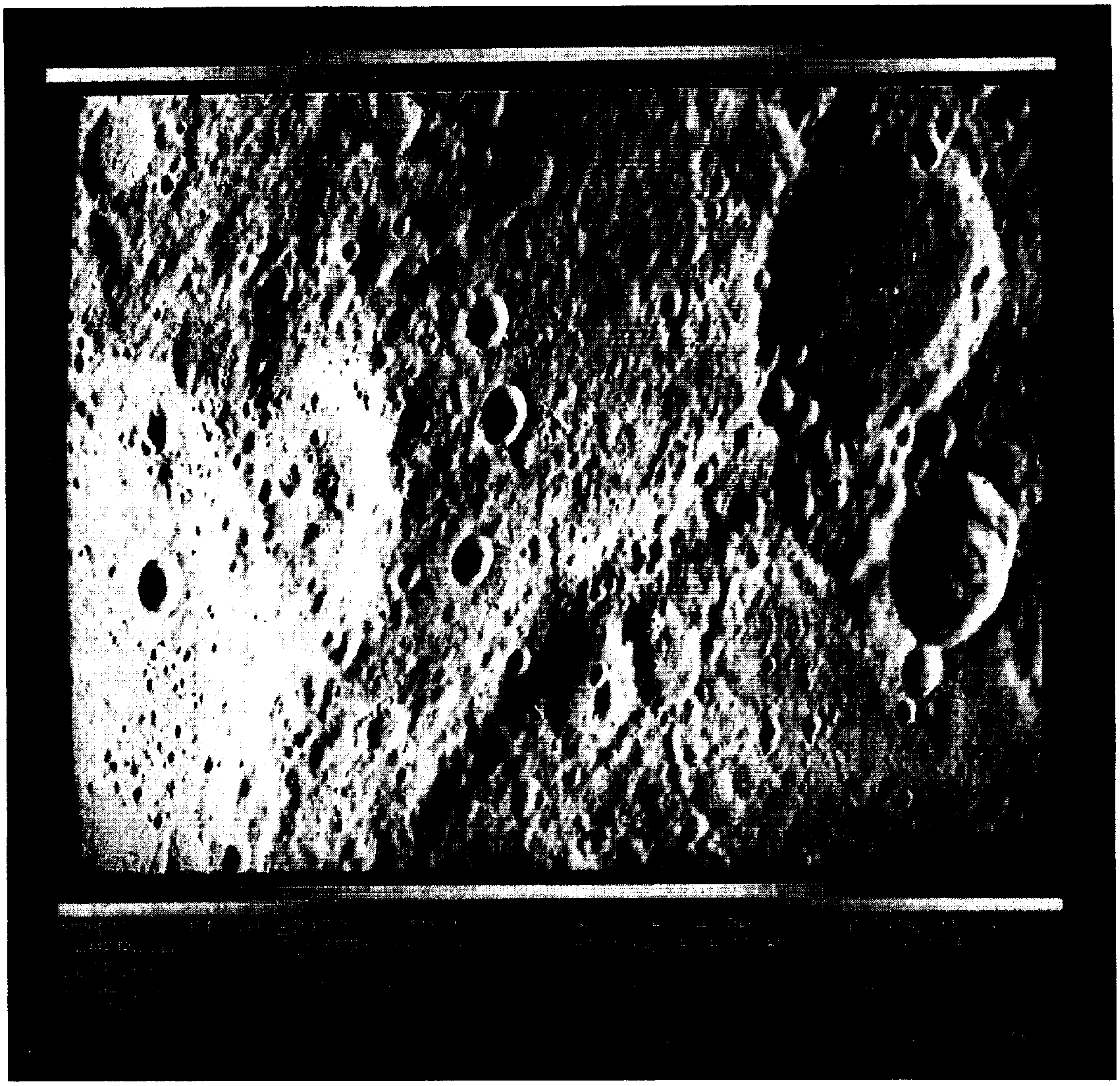
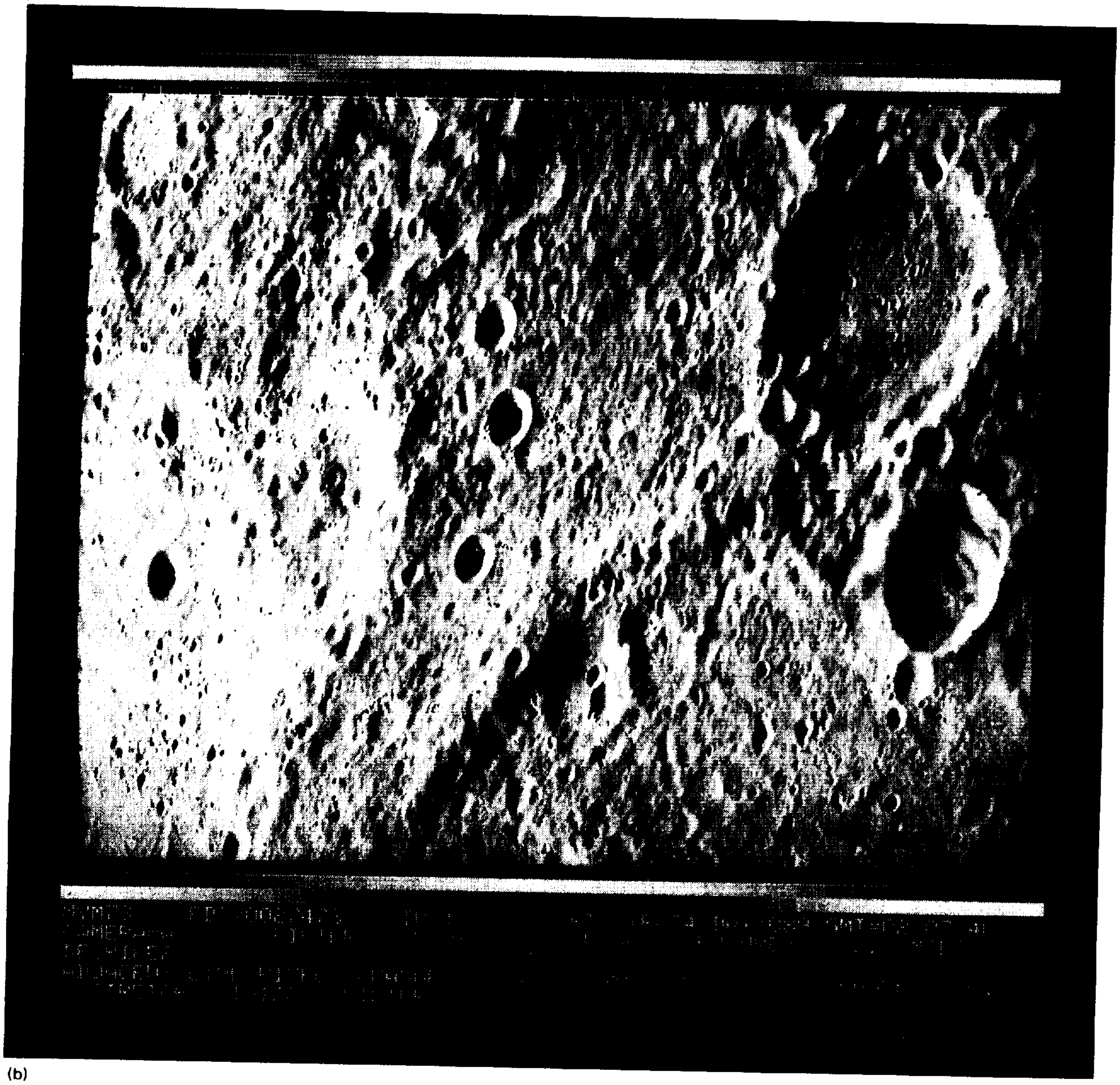


Fig. B-3. Three versions of a single picture of Mercury are compared: (a) the Digifax system, (b) the MTC improved version, and (c) the IPL version.

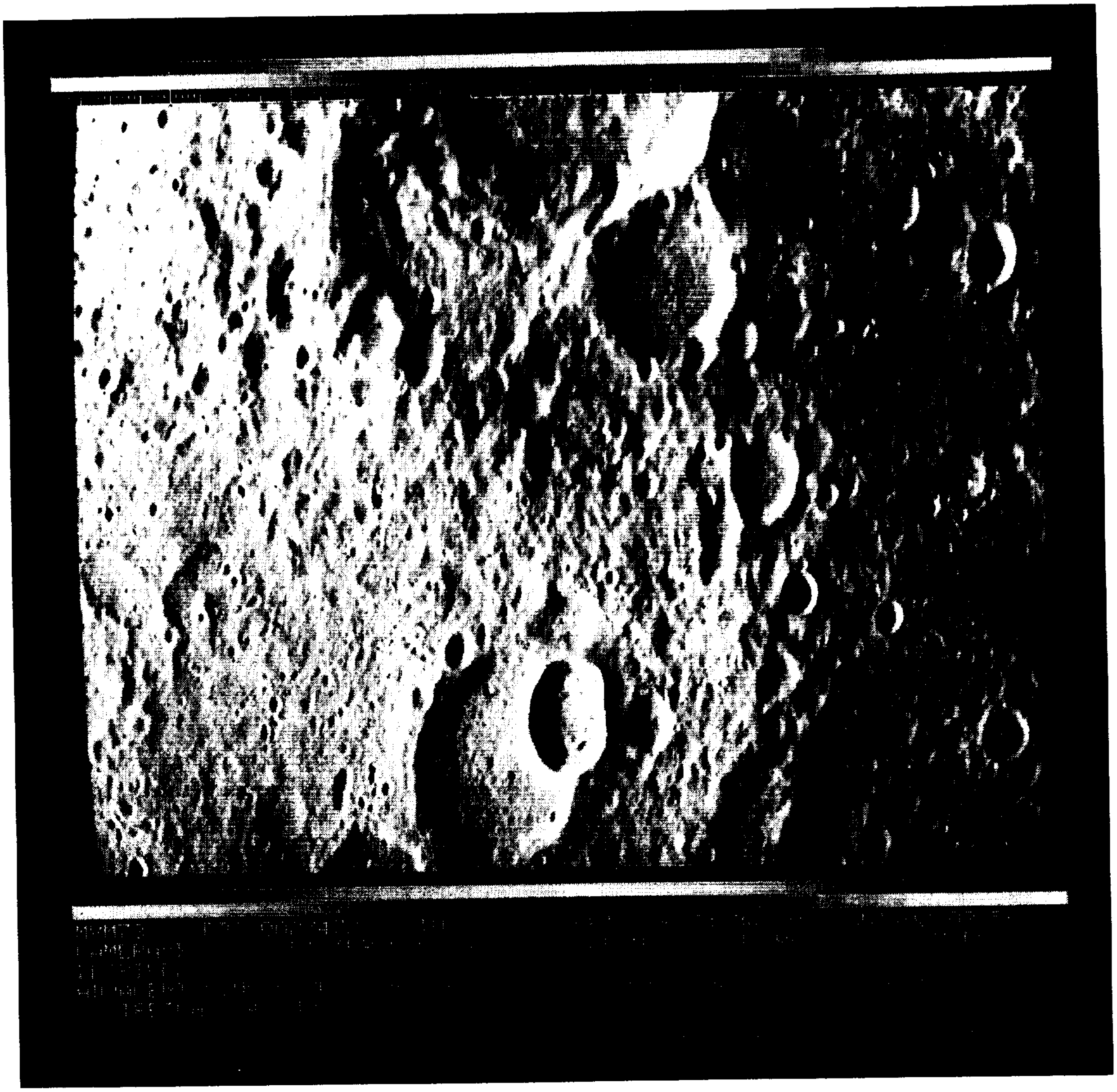


(a)

Fig. B-4. Comparison of images produced (a) from the experimenter data record and (b) from compensated data that correct for modulation characteristics of the electronics of the A-camera from which the image data were received.

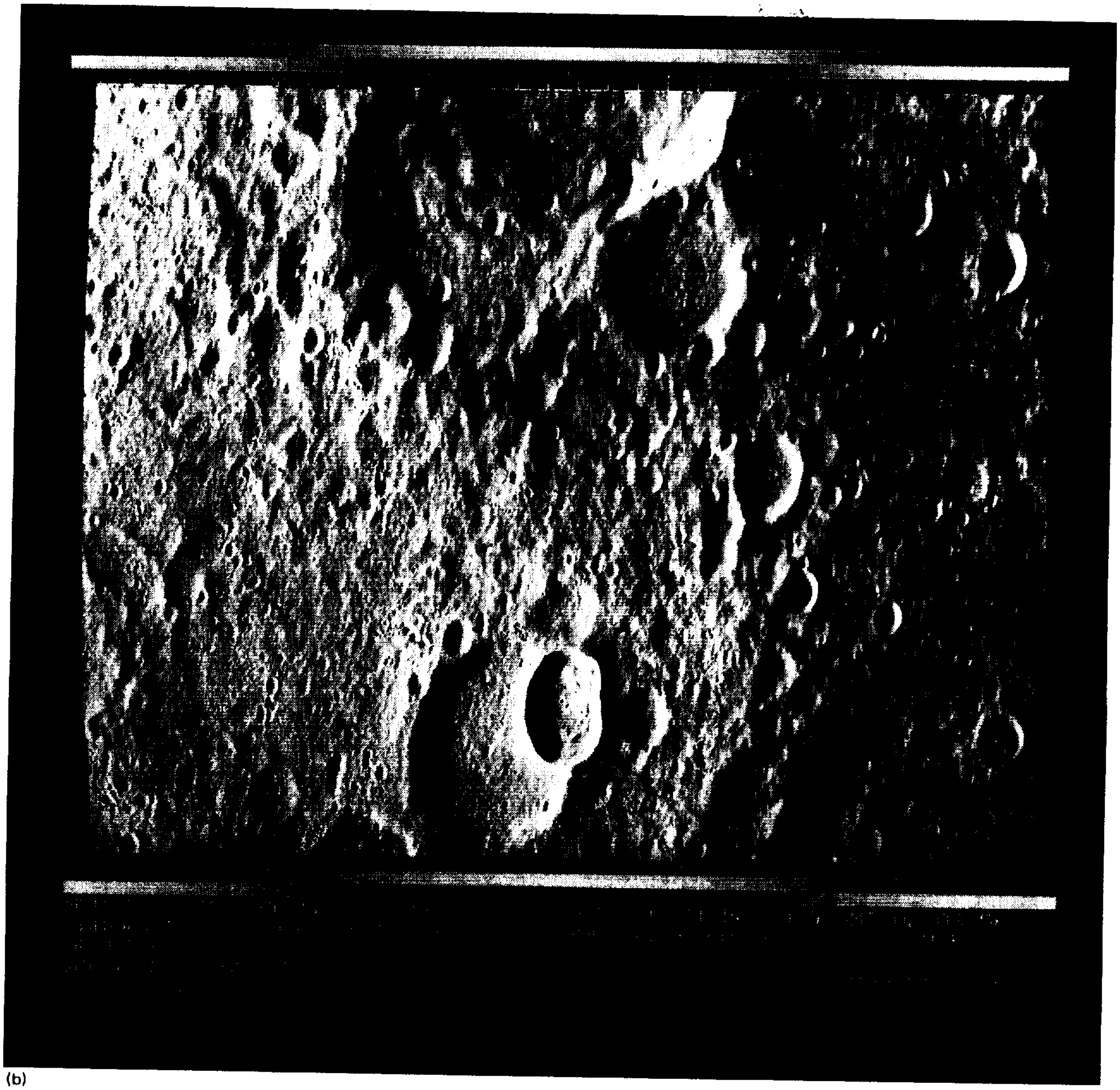


(b)

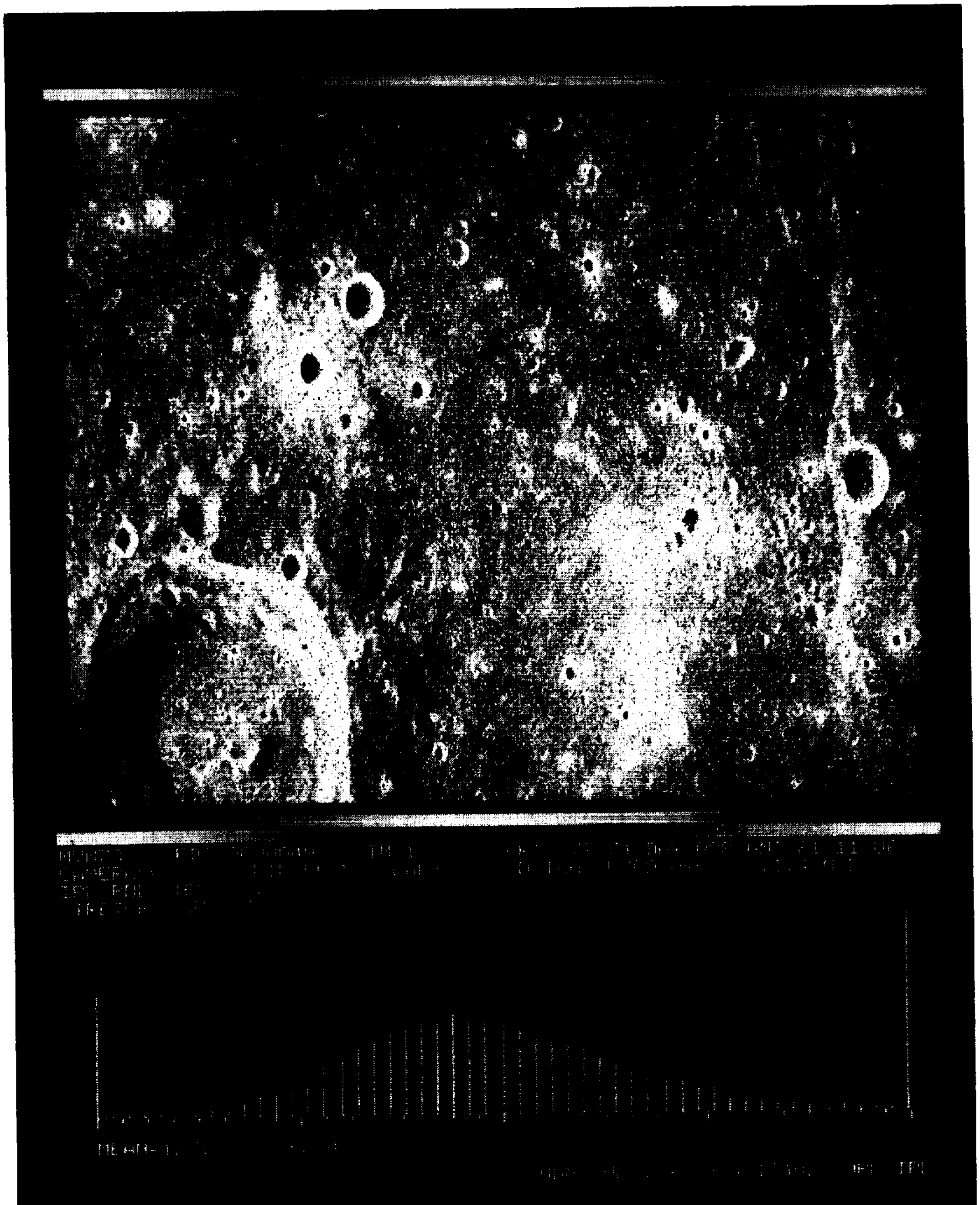


(a)

Fig. B-5. A similar pair of images from the B-camera are shown improved in the same way by convolutional filtering.

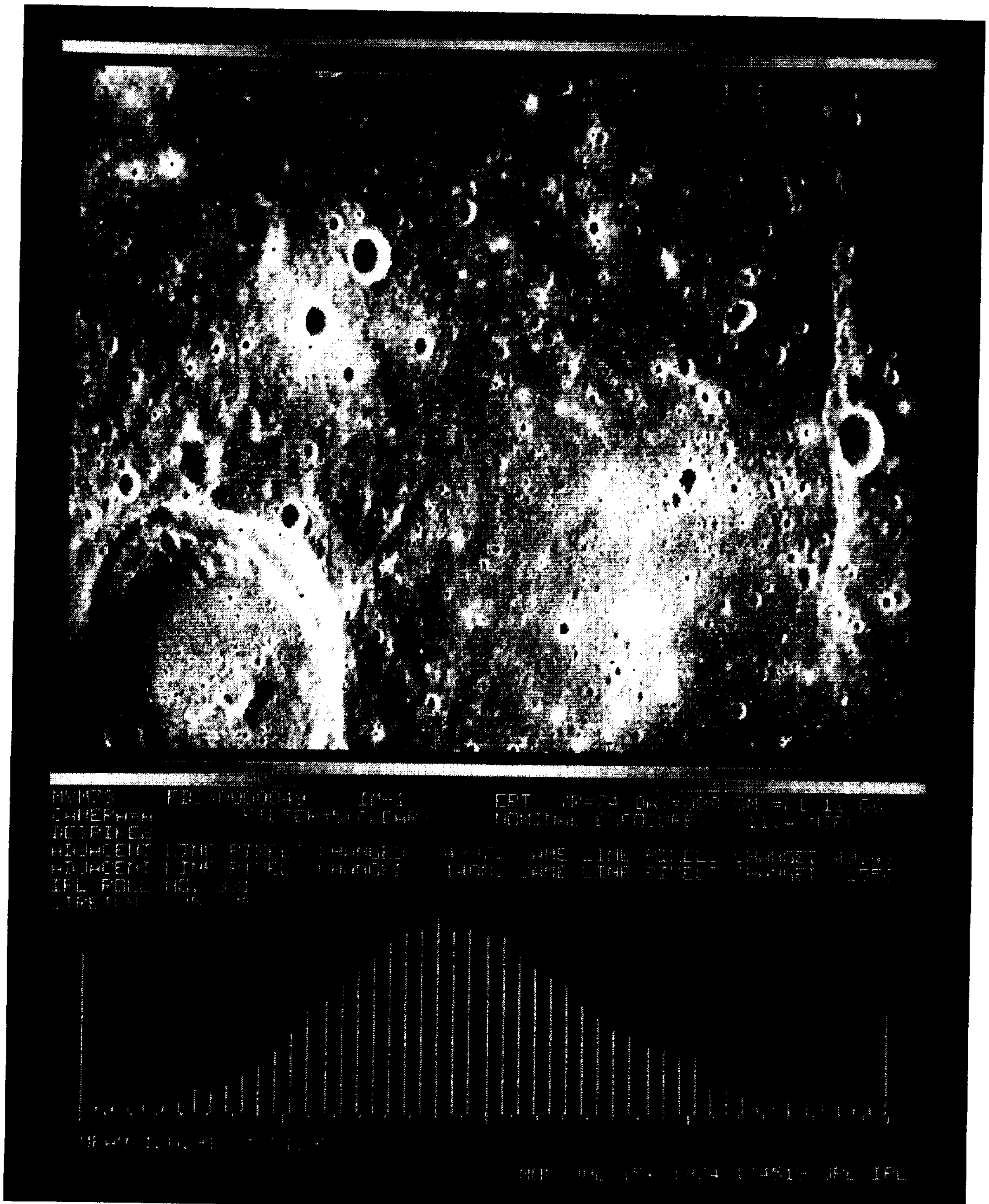


(b)

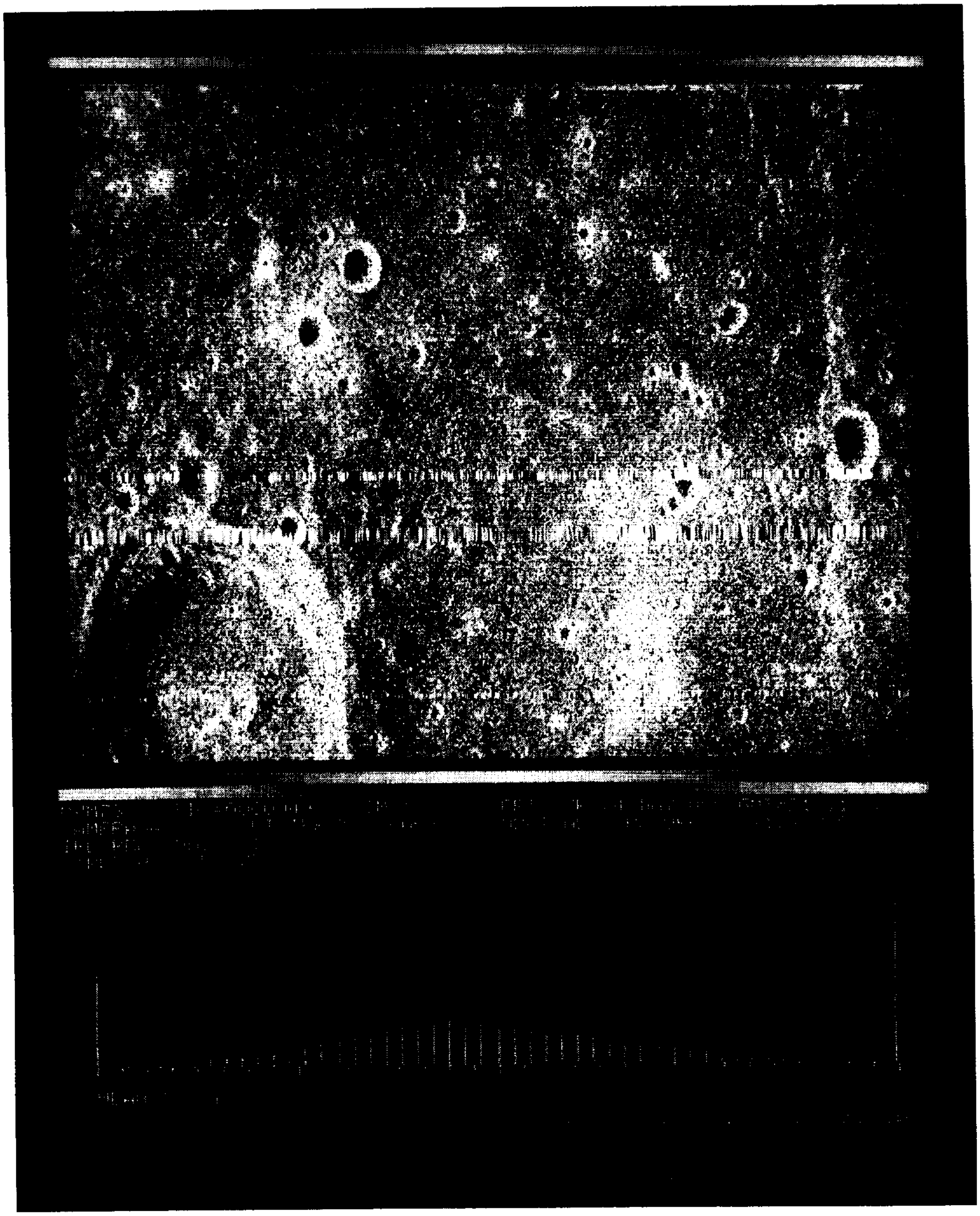


(a)

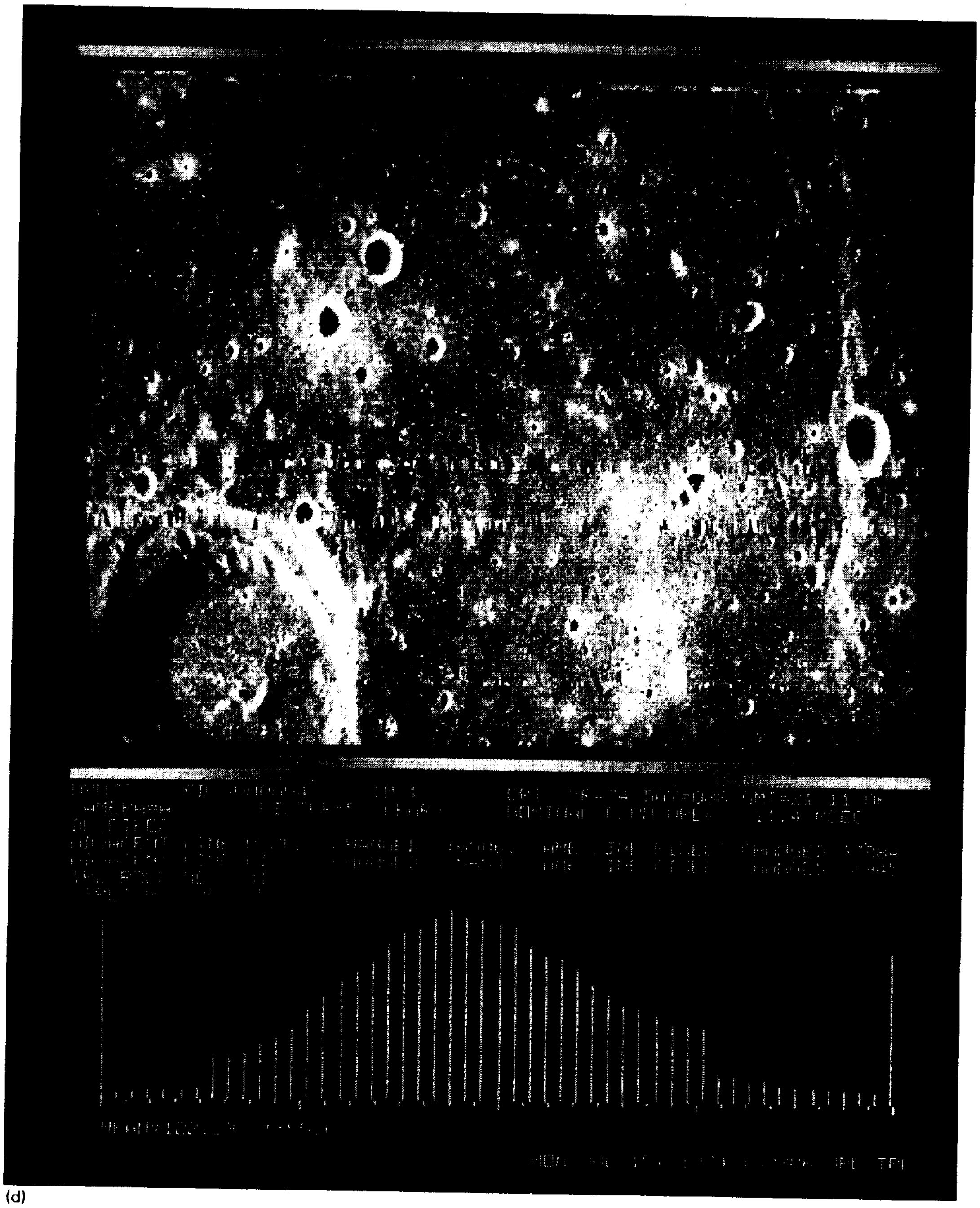
Fig. B-6. This series of pictures shows how the Image Processing Laboratory cleans up errors in real-time pictures: (a) a real-time picture with a bit error rate of 1 in 33; (b) the same picture after cleanup of 57,000 pixels in error; (c) the same frame received with an error rate of 1 in 14, and (d) when it has been cleaned up by 128,000 pixels; (e) a virtually error-free picture received later by tape playback from the spacecraft.



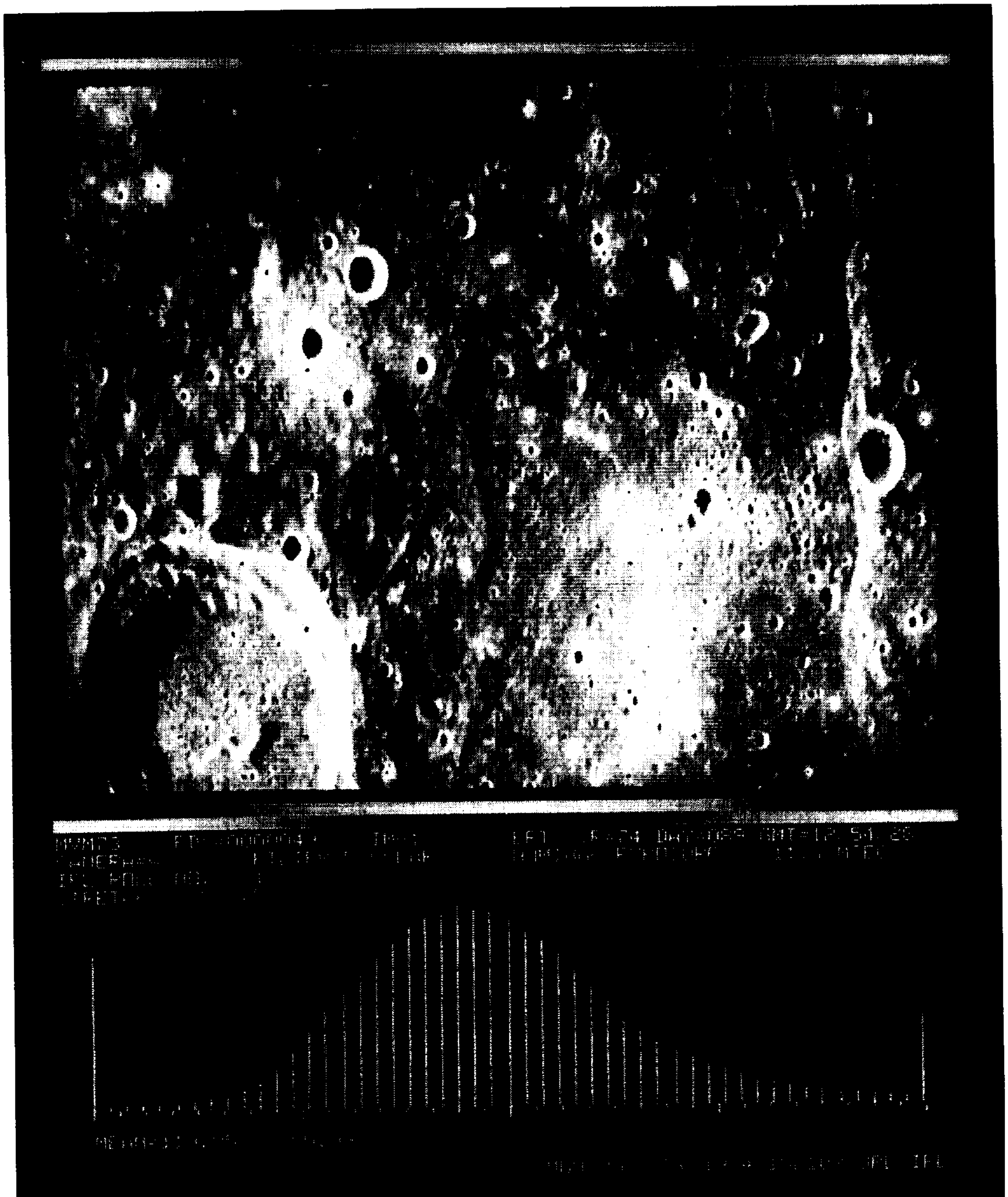
(b)



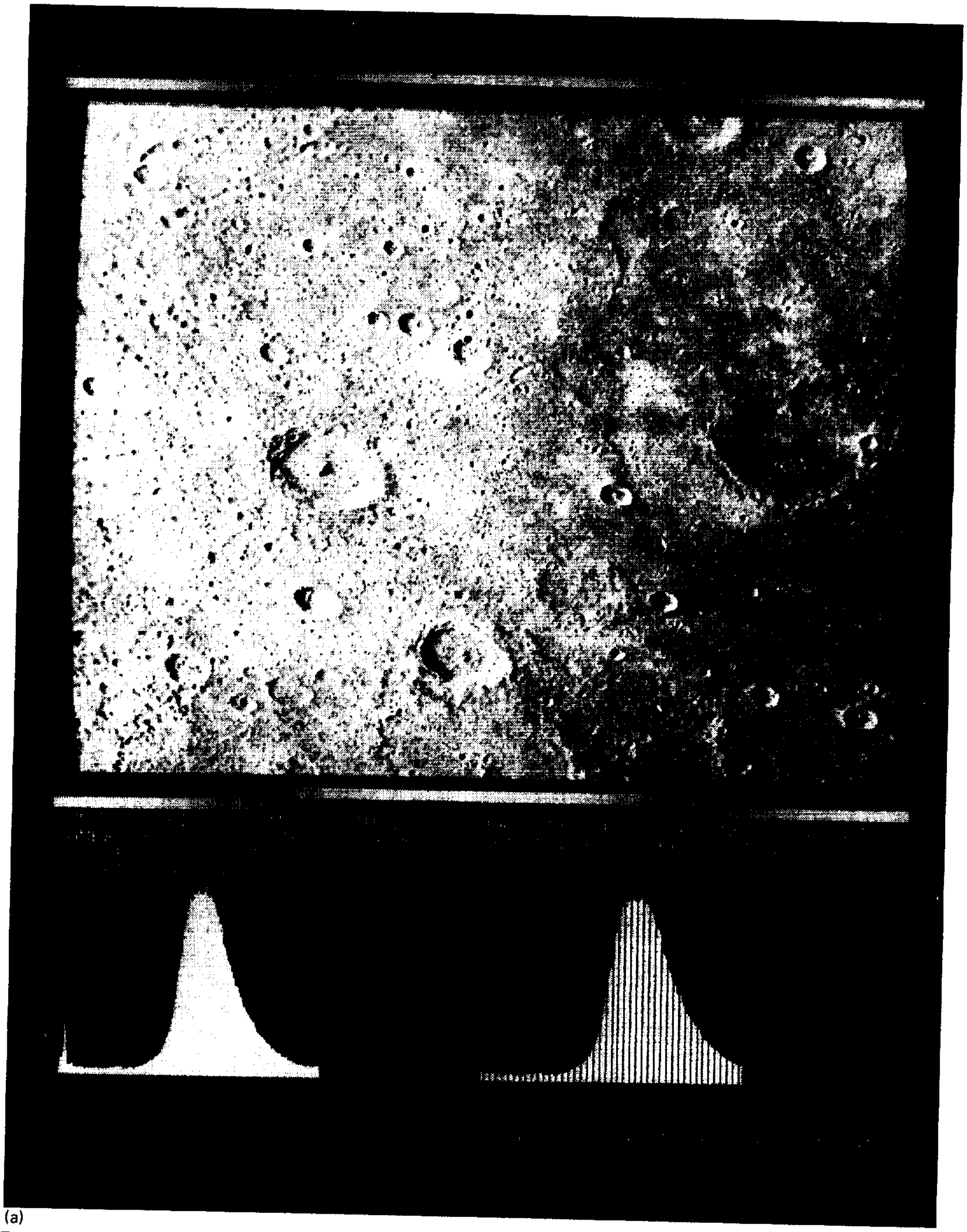
(c)



(d)

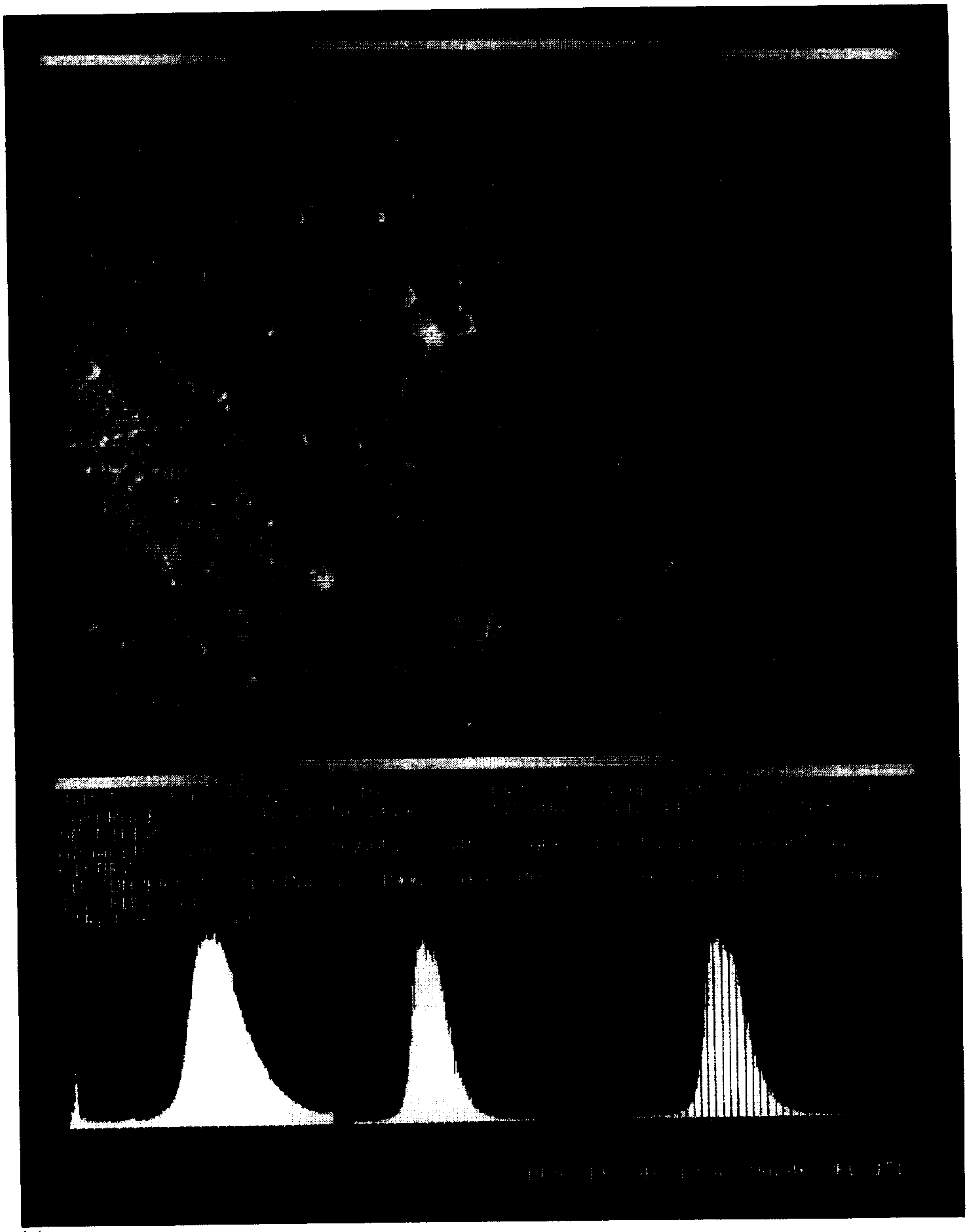


(e)

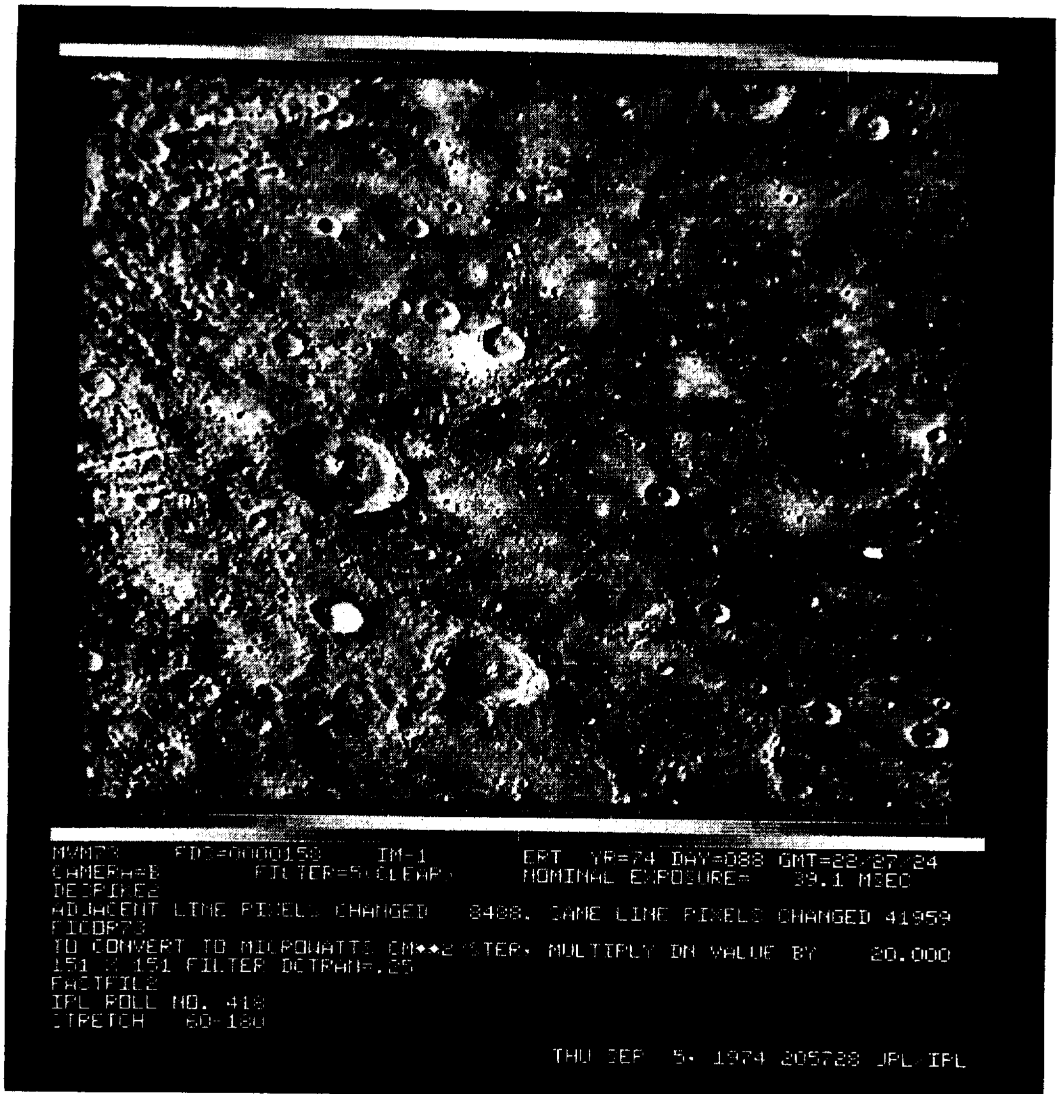


(a)

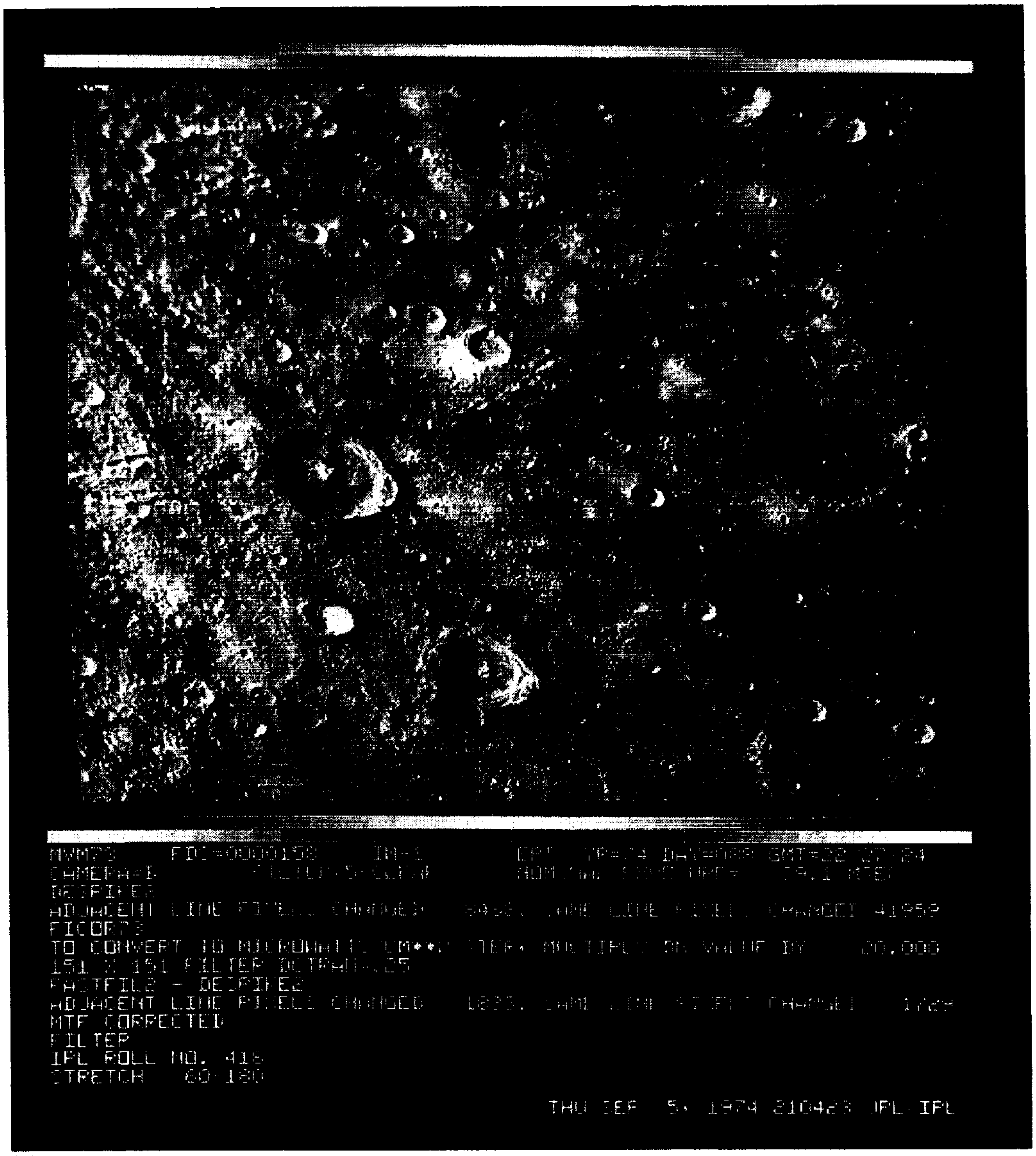
Fig. B-7. This series shows another method of removing errors from real-time pictures: (a) a picture received from Canberra with typical pixel errors showing as black dots; (b) the picture processed to remove the errors and to correct for some distortion in the camera; (c) the effect of a high-pass filter to increase contrast two times; (d) a further correction to eliminate a camera electronic distortion; (e) the corrected picture reprojected for assembly into a large-scale mosaic of the type shown in Appendix A.



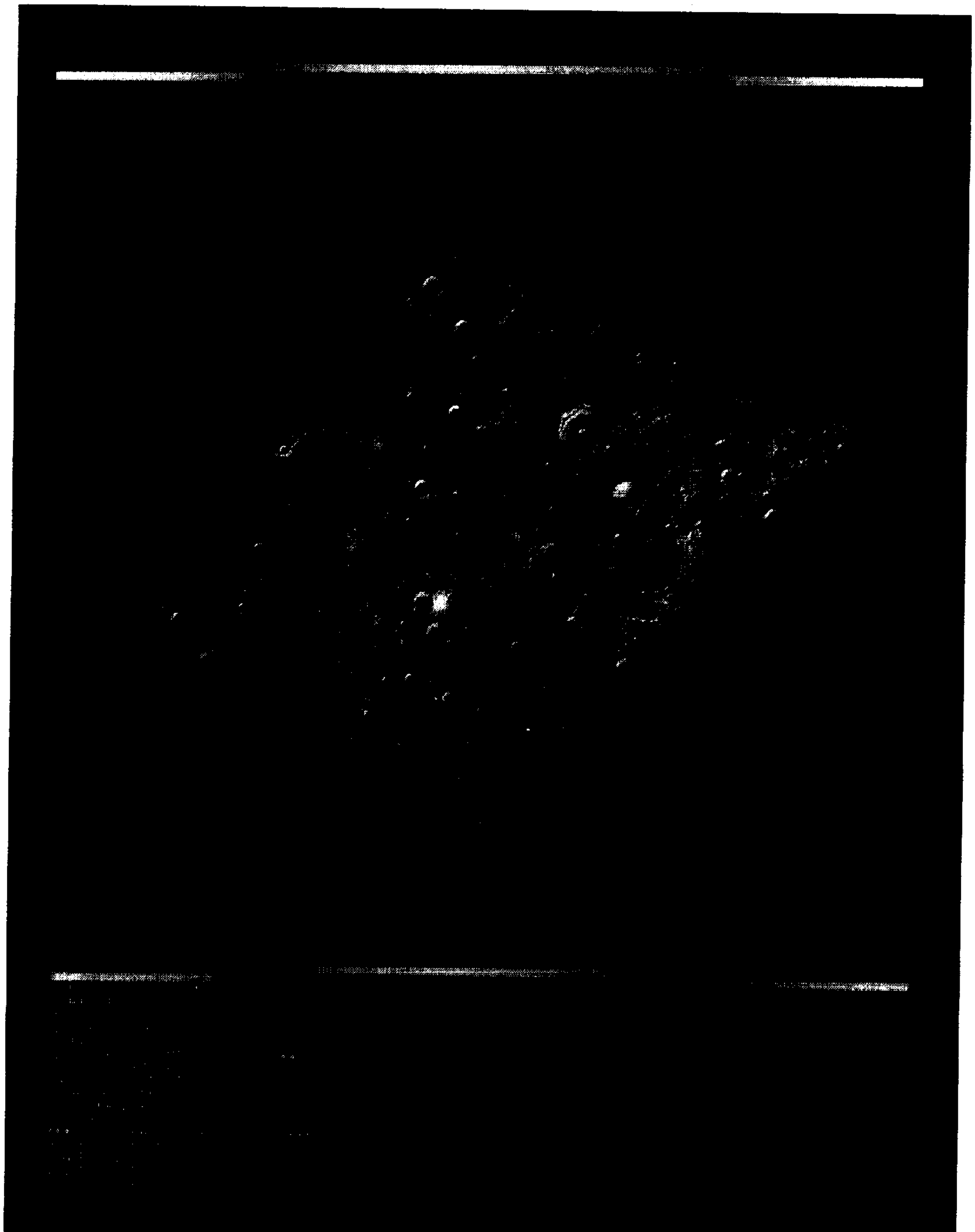
(b)


MVM73 FDS=0000158 IM-1
ERT YR=74 DAY=088 GMT=22/27/24
CAMERA=B FILTER=5(CLEAR)
NOMINAL EXPOSURE= 39.1 MSEC
DESPIKE2
ADJACENT LINE PIXELS CHANGED 8408. SAME LINE PIXELS CHANGED 41959
FICOR73
TO CONVERT TO MICROWATTS CM**2/STER, MULTIPLY DN VALUE BY 20.000
151 X 151 FILTER DCTRAN=.25
FACTFIL2
IPL ROLL NO. 418
STRETCH 60-180
THU SEP 5, 1974 205728 JPL/IPL

(c)



(d)



(e)

Fig. B-8. This mosaic has been assembled from frames that were processed with normal contrast. The result is loss of detail in the terminator region.

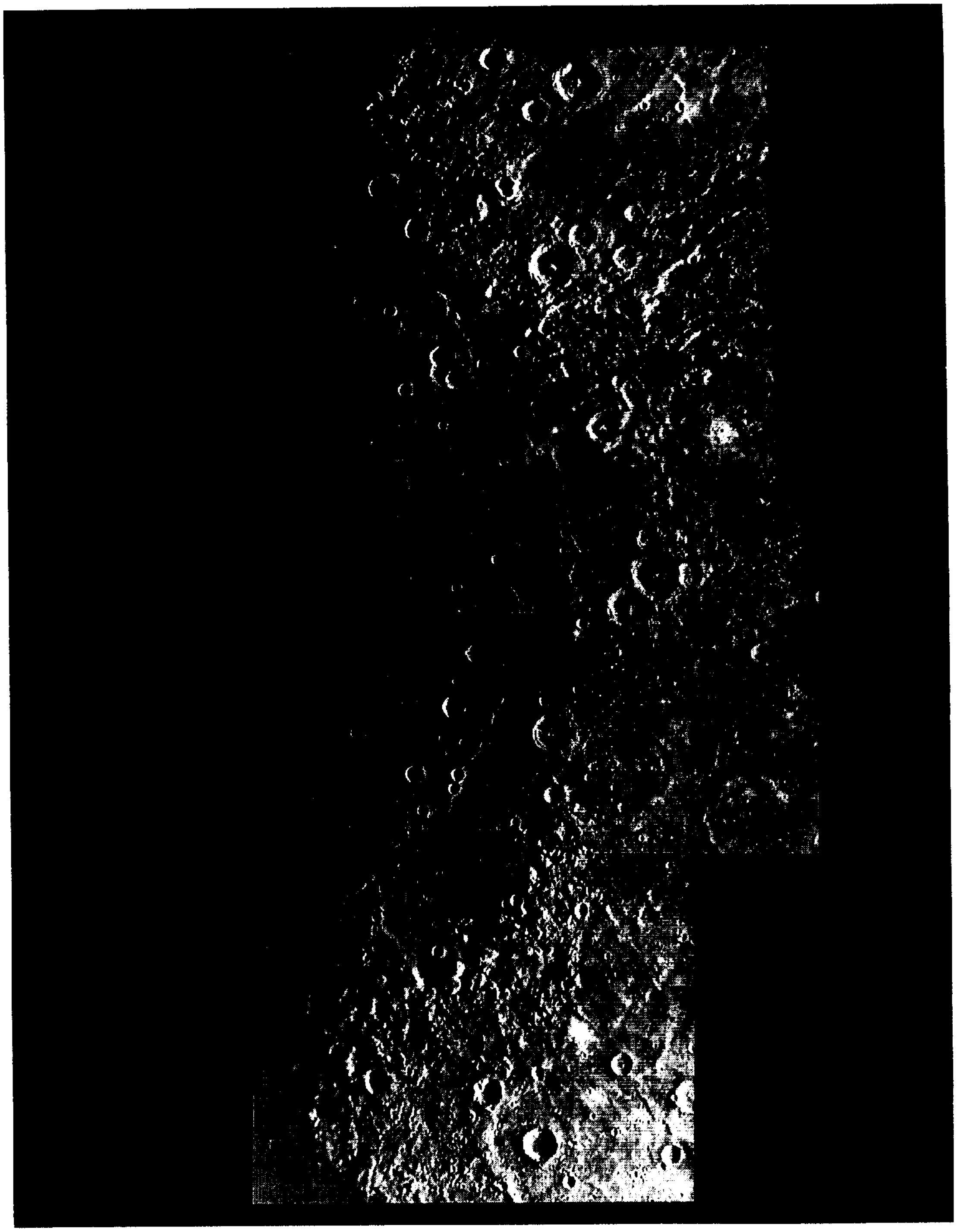
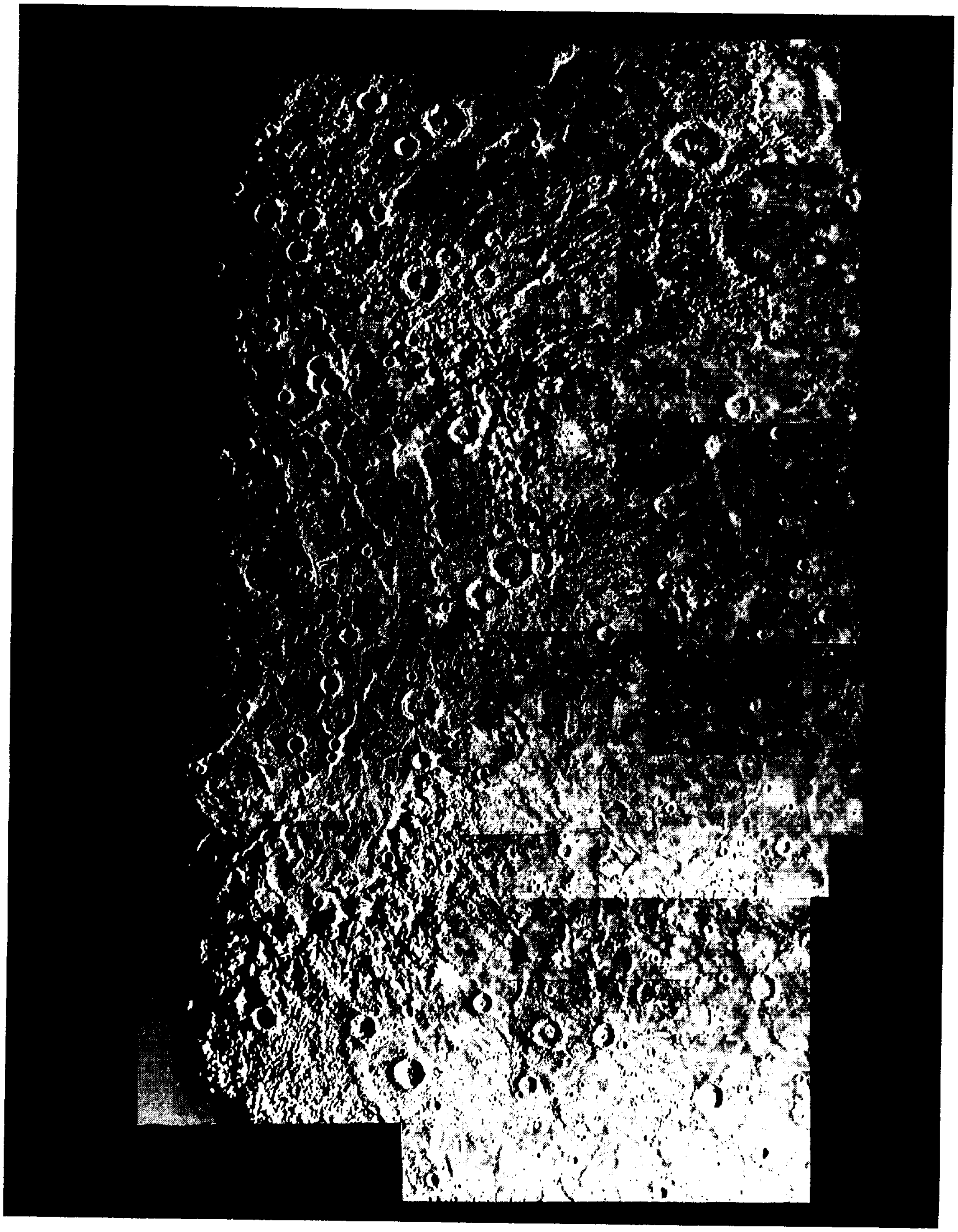
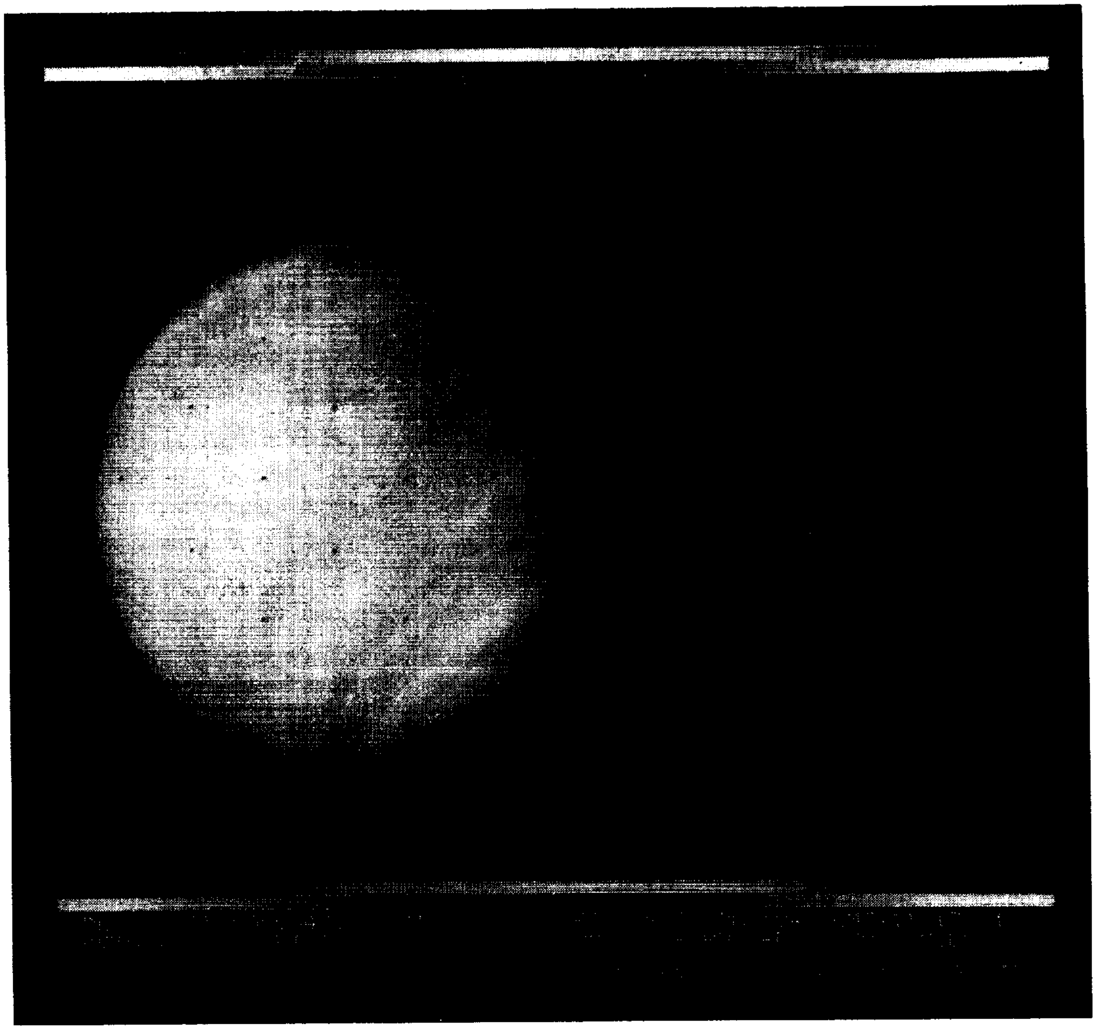


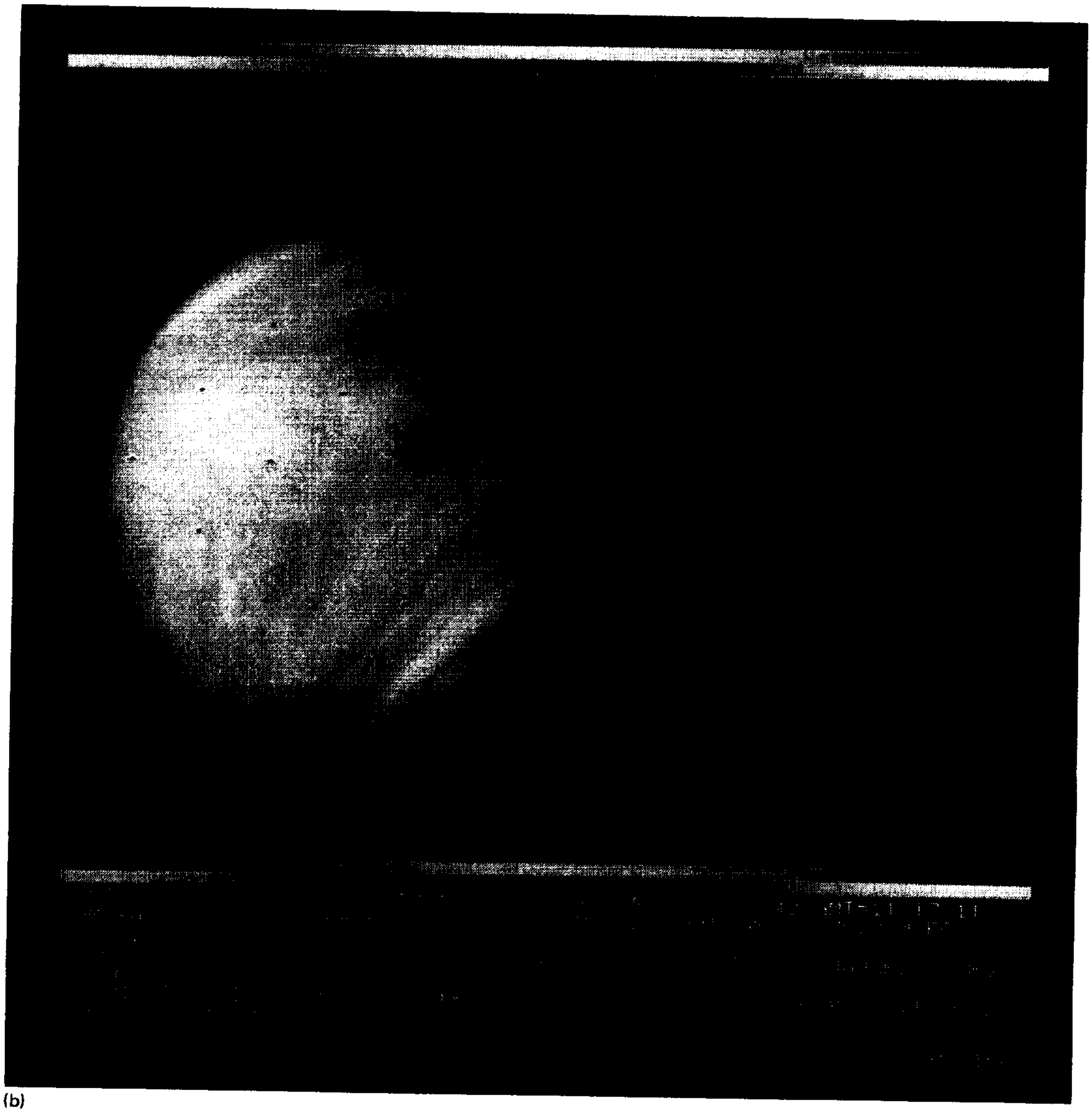
Fig. B-9. This same region is here reproduced from frames that were processed through spatially dependent filtering to improve the visibility of features in the region of the terminator.



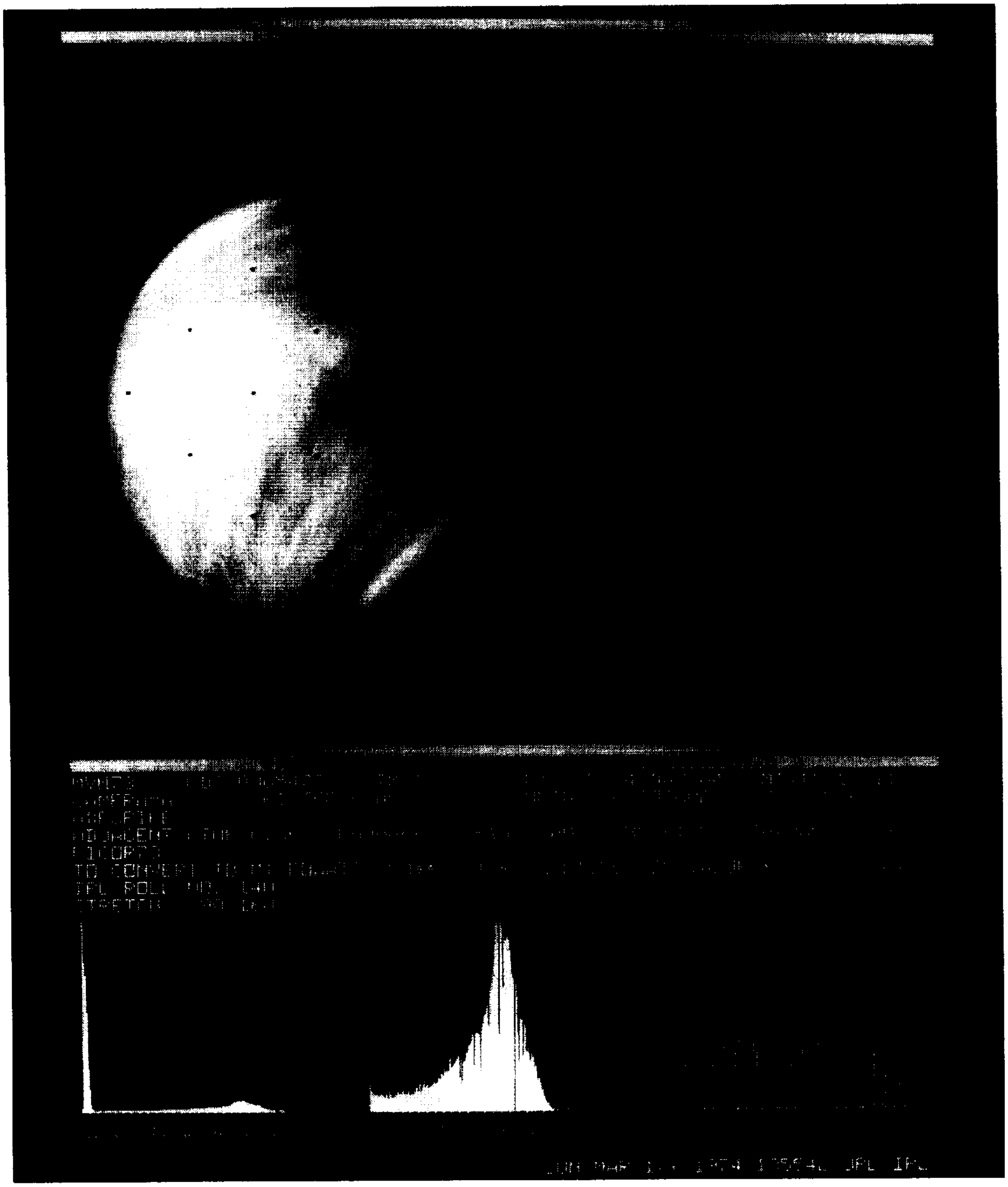


(a)

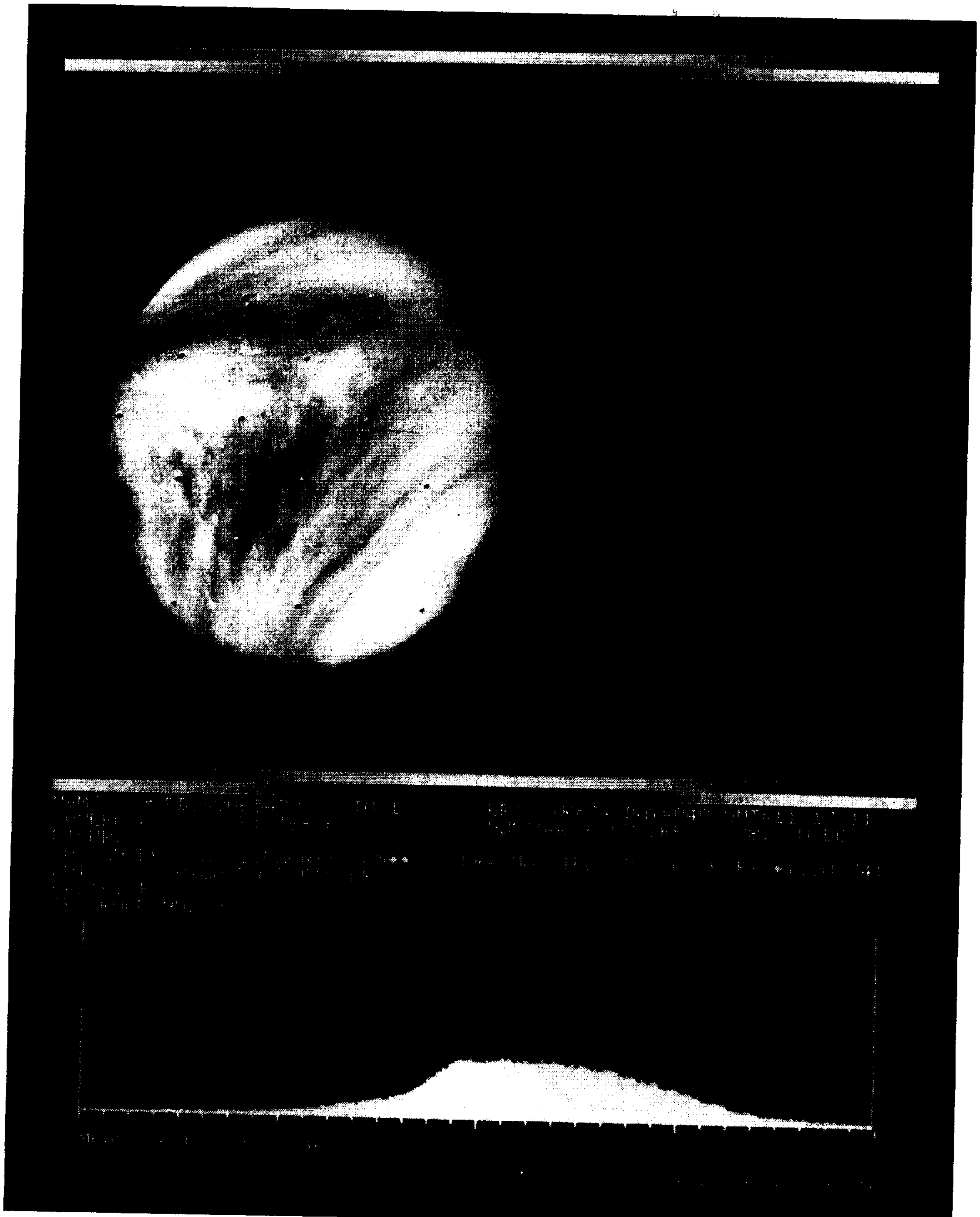
Fig. B-10. This series of images shows how cloud structure can be enhanced by computer processing: (a) the uncorrected raw image of Venus; (b) the errors introduced by the camera of the spacecraft have been taken out and the contrast of the image has been increased 1.5 times; (c) the contrast is further increased 3.5 times; (d) global shading has been removed to present more even illumination over the whole of the planet, and the contrast has also been further increased; (e) a further step in increasing contrast; (f) and (g) images processed through high-pass filters to emphasize small-scale cloud details.



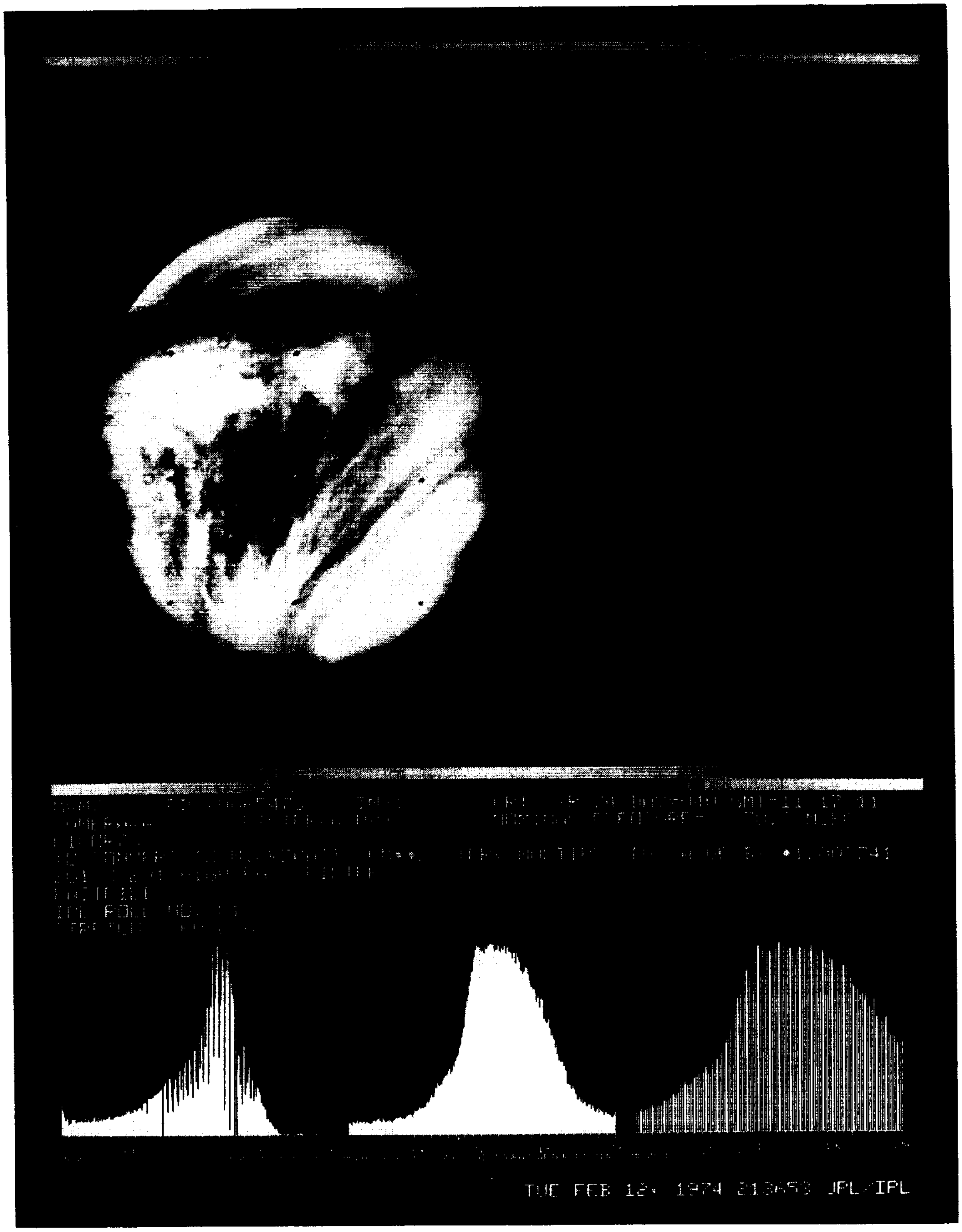
(b)



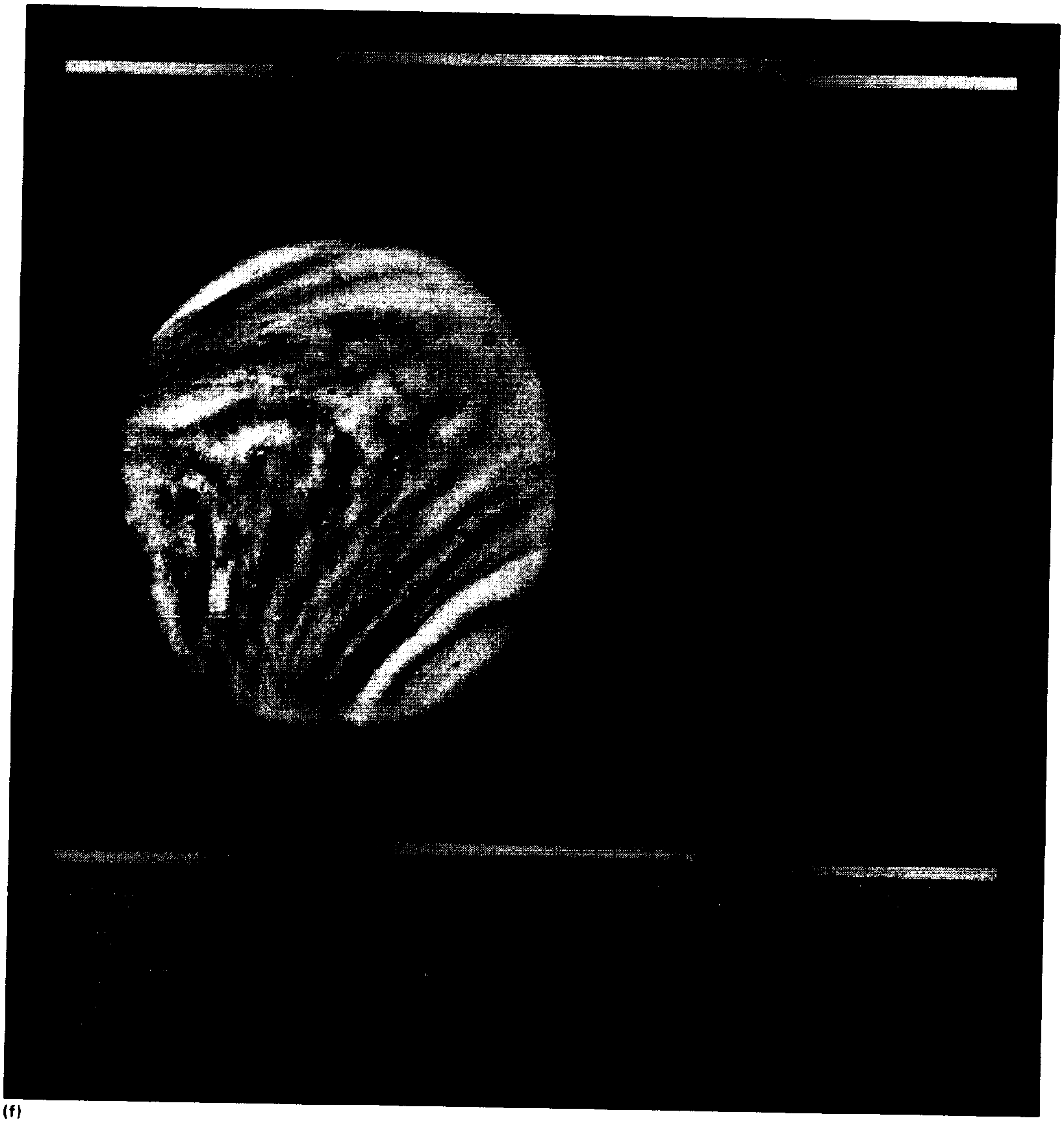
(c)



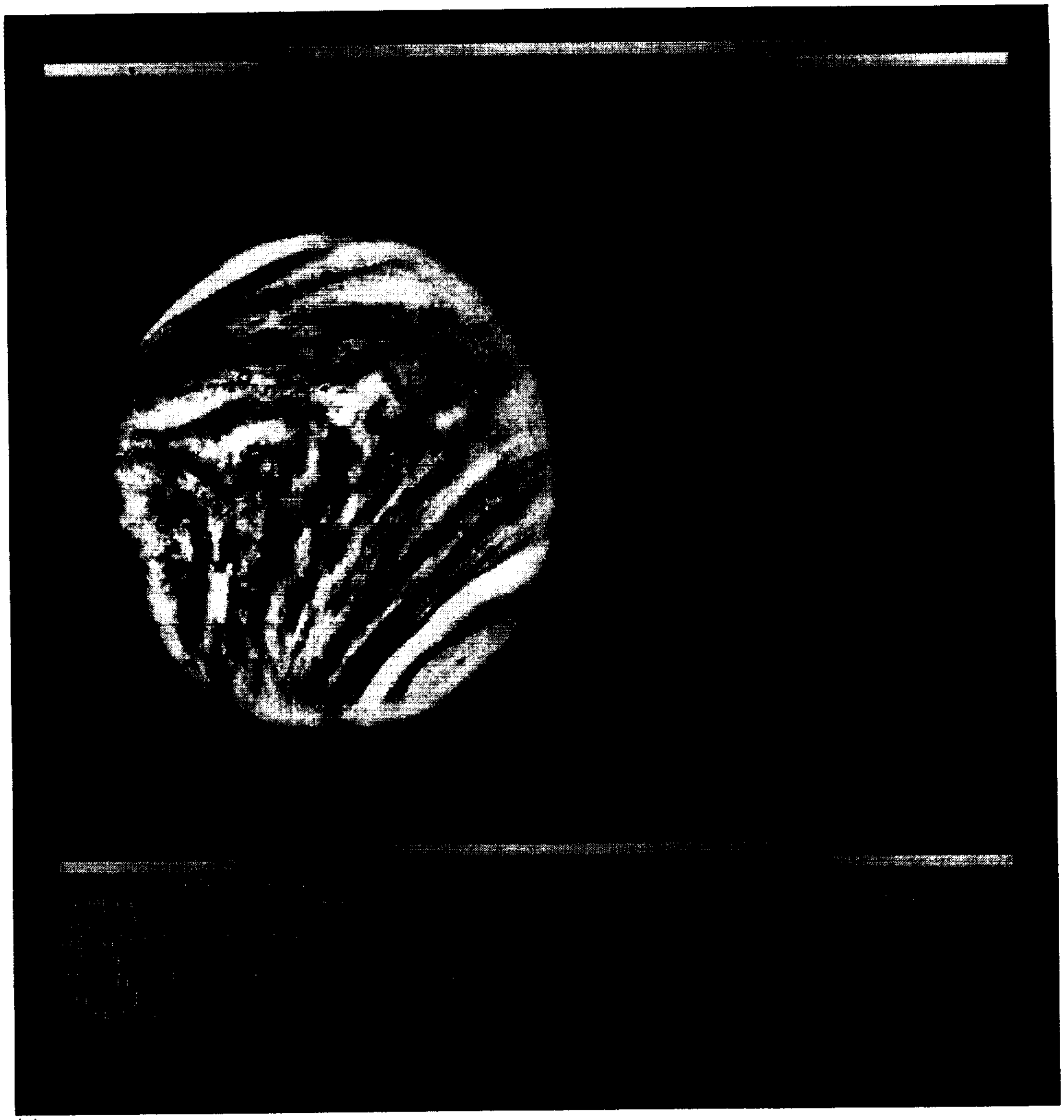
(d)



(e)



(f)



(g)

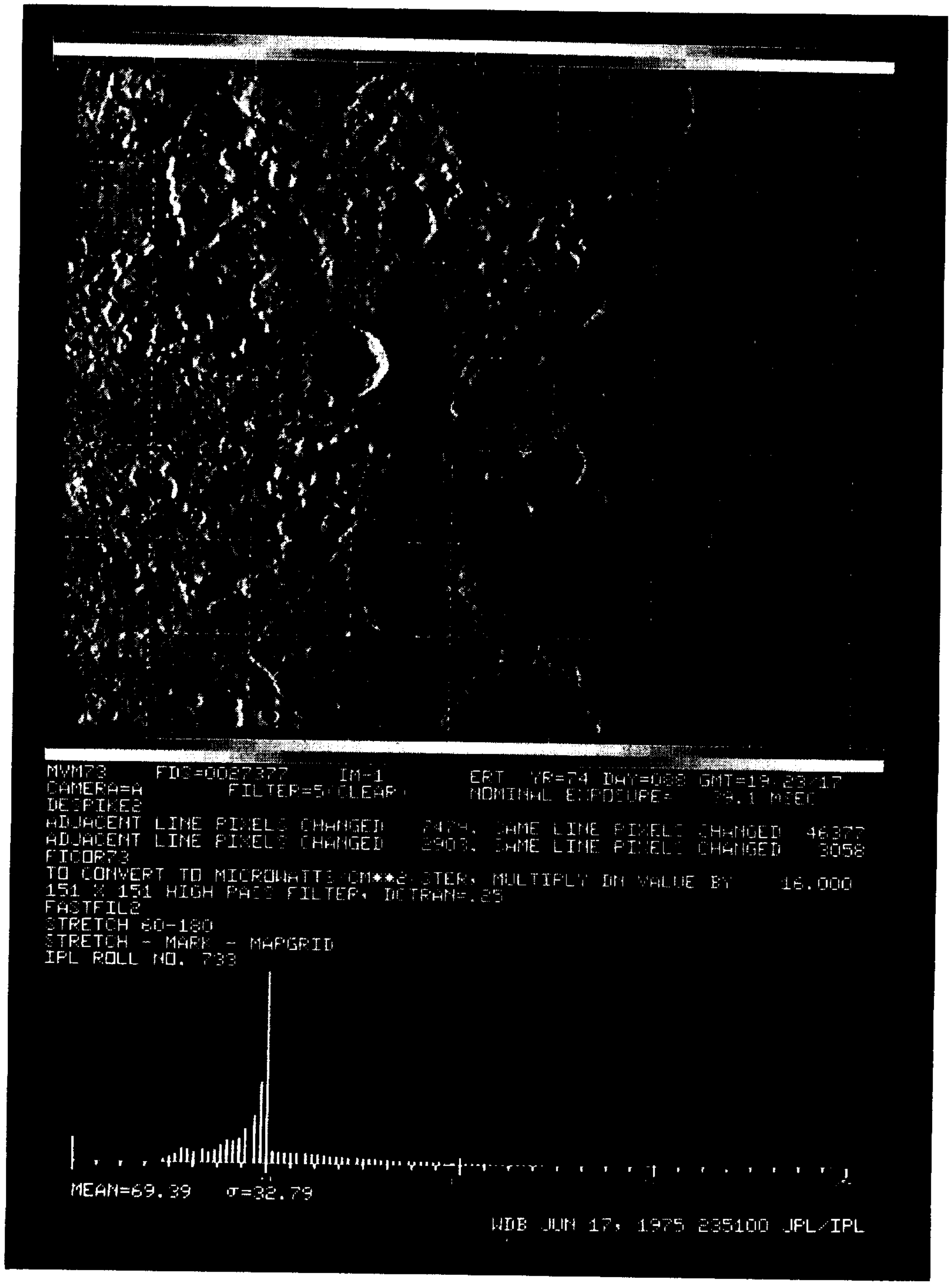


Fig. B-11. Special versions of pictures were also made on which black and white dots are introduced every 25 pixels in the form of a grid on the picture as shown here. By counting pixels on pictures such as this, the coordinates of control points on Mercury's surface were established as part of the map-making process.

Appendix C
Spacecraft and Science Teams

Mariner 10 Project Management

Office of Space Science, NASA Headquarters, Washington, D.C.

John E. Naugle	Associate Administrator for OSS
Vincent L. Johnson	Deputy Associate Administrator for OSS
Robert S. Kraemer	Director, Planetary Programs
Ichtiaque Rasool	Deputy Director, Planetary Programs
N. William Cunningham	Program Manager
Gunther Strobel	Program Engineer
Stephen E. Dwornik	Program Scientist
Joseph B. Mahon	Director, Launch Vehicle Programs
T. Bland Norris	Manager, Medium Launch Vehicles
F. Robert Schmidt	Manager, Atlas-Centaur

Office of Tracking and Data Acquisition, NASA Headquarters, Washington, D.C.

Gerald M. Truszynski	Associate Administrator for OTDA
Arnold C. Belcher	Network Operations
Maurice E. Binkley	Network Support

Jet Propulsion Laboratory, Pasadena, California

William H. Pickering	Laboratory Director
Charles H. Terhune, Jr.	Deputy Laboratory Director
Robert J. Parks	Assistant Laboratory Director for Flight Projects
Walker E. Giberson	Project Manager
John R. Casani	Spacecraft System Manager
James N. Wilson	Assistant Spacecraft System Manager
Norri Sirri	Mission Operations System Manager
Victor C. Clarke, Jr.	Mission Analysis and Engineering Manager
James A. Dunne	Project Scientist
Clayne M. Yeates	Assistant Project Scientist
Nicholas A. Renzetti	Tracking and Data System Manager
Esker K. Davis	Deep Space Network Manager
Gael F. Squibb	Chief of Mission Operations
Dallas F. Beauchamp	Deputy Chief of Mission Operations

Lewis Research Center, Cleveland, Ohio

Bruce T. Lundin .... Center Director
Edmund R. Jonash .... Director, Launch Vehicles
W.R. Dunbar .... Deputy Director, Launch Vehicles
Daniel J. Shramo .... Atlas-Centaur Project Manager
Rodney M. Knight .... Center Project Engineer

Kennedy Space Center, Florida

Kurt H. Debus .... Center Director
John J. Neilon .... Director, Unmanned Launch Operations, ULO
John D. Gossett .... Chief, Centaur Operations Branch, ULO
Donald C. Sheppard .... Chief, Spacecraft Operations Branch, ULO
James E. Weir .... Spacecraft Operations Engineer

Boeing Company, Kent, Washington

Edwin G. Czarnecki .... Project Manager
Haim Kennet .... Deputy Project Manager

Mariner 10 Project Staff

The project staff of the Mariner 10 program, together with those many people in industry and at NASA facilities and universities who jointly made this exploratory mission possible, received group achievement awards from NASA and are listed in Appendix D.

Experiments and Investigators

Television Experiment

Team Leader:

Bruce C. Murray
California Institute of Technology

Team Members:

Michael J. S. Belton
Kitt Peak National Observatory

G. Edward Danielson, Jr.
Jet Propulsion Laboratory

Merton E. Davies
Rand Corporation

Bruce Hapke
University of Pittsburgh

Brian T. O'Leary
Hampshire College

Robert Strom
University of Arizona

Verner E. Suomi
University of Wisconsin

Newell J. Trask
U.S. Geological Survey

Associate Team Members:

James L. Anderson
California Institute of Technology

A. Dollfus
Observatoire de Paris

Donald E. Gault
NASA Ames Research Center

John Guest
University of London Observatory

Robert Krauss
University of Wisconsin

Gerard P. Kuiper
University of Arizona

Plasma Science Experiment

Principal Investigator:

Herbert S. Bridge
Massachusetts Institute of Technology

Co-Investigators:

J. Ashbridge
Samuel J. Bame
M. Montgomery
Los Alamos Scientific Laboratory

A. Hundhausen
University of Colorado

Leonard Burlaga
R. E. Hartle
Keith W. Ogilvie
NASA Goddard Space Flight Center

J. H. Binsack
A. J. Lazarus
S. Olbert
Massachusetts Institute of Technology

Clayne M. Yeates
Jet Propulsion Laboratory

George L. Siscoe
University of California at Los Angeles

Ultraviolet Spectroscopy Experiment

Principal Investigator:

A. Lyle Broadfoot
Kitt Peak National Observatory

Co-Investigators:

M. B. McElroy
Harvard University

Michael J. S. Belton
Kitt Peak National Observatory

Infrared Radiometry Experiment

Principal Investigator:

Stillman C. Chase, Jr.
Santa Barbara Research Center

Co-Investigators:

Ellis D. Miner
Jet Propulsion Laboratory

David Morrison
University of Hawaii

Gerry Neugebauer
California Institute of Technology

Charged Particles Experiment

Principal Investigator:

John A. Simpson
University of Chicago

Co-Investigator:

J. E. Lamport
University of Chicago

Radio Science Experiment

Team Leader:

H. T. Howard
Stanford University

Team Members:

Irwin I. Shapiro
Massachusetts Institute of Technology

John D. Anderson
Gunnar Fjeldbo
Arvydas J. Kliore
Gerald S. Levy
Jet Propulsion Laboratory

Associate Team Members:

G. Tyler
Stanford University

R. D. Reasenberg
Massachusetts Institute of Technology

D. Lee Brunn
Richard Dickinson
Robert E. Edelson
Pasquale B. Esposito
Charles T. Stelzried
Jet Propulsion Laboratory

Magnetic Fields Experiment

Principal Investigator:

Norman F. Ness
NASA Goddard Space Flight Center

Co-Investigators:

Kenneth W. Behannon
Ronald P. Lepping
J. Scheifele
NASA Goddard Space Flight Center

Kenneth H. Schatten
Victoria University, Wellington, New Zealand

Y. C. Whang
Catholic University

Mariner 10 Key Subcontractors

Spacecraft system and support

The Boeing Company
Kent, Washington

Spacecraft Engineering Hardware

Celestial sensors

Honeywell Radiation Center
Lexington, Massachusetts

Data storage tape transport

Lockheed Electronics Co.
Plainfield, New Jersey

Radio frequency subsystem, flight data subsystem

Motorola, Inc., Government Electronics Division
Scottsdale, Arizona

Data storage subsystem, flight command unit, telemetry modulation unit

Texas Instruments, Equipment Group
Dallas, Texas

Power subsystem

Xerox Corp., Electro-Optical Systems
Pasadena, California

Flight batteries

TRW Systems Group
Redondo Beach, California

Reaction control jet nozzle assemblies

Sterer Engineering and Manufacturing Co.
Los Angeles, California

Electronic parts screening

General Electric, Space Division
Valley Forge, Pennsylvania

Solar cells

Centralab, Semiconductor Division of Globe-Union Inc.
El Monte, California

Printed circuit boards

Innovative Electronics
Monrovia, California

Solar cell glass cover filters

Optical Coating Laboratory, Inc.
Santa Rosa, California

TWT amplifiers

Watkins-Johnson
Palo Alto, California

Science Instruments

Infrared radiometer

Santa Barbara Research Center
Goleta, California

Television

Xerox Corp., Electro-Optical Systems
Pasadena, California

Appendix D Mariner 10 Award Recipients

On Friday, August 16, 1974, Dr. William H. Pickering, Director of the Jet Propulsion Laboratory, welcomed guests to a special awards ceremony following the successful completion of the nominal mission of Mariner 10 to Mercury via Venus:

"We are honored today in welcoming Dr. James Fletcher, Administrator of NASA, and our distinguished guests to an awards ceremony that offers special recognition to those individuals and teams who have contributed outstandingly to the mission of Mariner 10 to Venus and Mercury. The Venus/Mercury 1973 Project has added another notable chapter to the 12-year story of Mariner – a spacecraft that has led the way in exploring the near planets of the Solar System.

"The Jet Propulsion Laboratory and the California Institute of Technology are proud of you awardees. You have demonstrated high professional competence and brought great credit to yourselves and to our institution. Congratulations on a job well done."

In presenting the awards, Dr. James Fletcher emphasized the importance of Mariner 10 in planetary exploration and in demonstrating how an advanced scientific project can be accomplished within cost goals:

"The Mariner 10 Awards Ceremony we are holding today recognizes the splendid achievements of the NASA-Industry-University team in the Mariner Venus/Mercury 1973 mission. Mariner 10 will be remembered in history as an engineering triumph which gave mankind unique television pictures and other scientific data from two distant planets. But we know that these accomplishments were the result of human endeavor and today we pay tribute to it as a human triumph by honoring some of the men and women who made Mariner 10 the success that it was.

"As a scientific achievement in interplanetary scientific exploration, Mariner 10 is adding to the laurels of the Mariner series of projects a new perspective on the planet Venus, our first close-up study of the planet Mercury, new observations of the interplanetary medium and the stars, and even some new data on the Moon. Although a full understanding of all the Mariner 10 scientific information will take years of study, it is already clear that we will gain valuable new insights on the two innermost planets. In addition to its direct scientific value, a better understanding of these planets will lead to a better understanding of our own Earth, its probable history, and its possible destiny.

"As a technical achievement of space engineering, the Mariner 10 mission broke new ground in interplanetary flight. It was the first flight demonstration of the gravity-assist technique, a promising propulsion aid for future missions. The two-planet flight plan called for a new degree of navigation accuracy, with Mariner 10 being directed within seven miles of its aiming point at Venus. The spacecraft passed within 416 miles of Mercury's surface, giving the experimenters excellent close-range planetary data; Mariner 10 is now en route to a second encounter with Mercury in September. The spacecraft successfully flew closer to the Sun than any man-made object ever has before. Finally, the adaptive nature of the mission and spacecraft permitted a number of in-flight modifications and additions to the scientific program.

"Mariner 10 was also a triumph of management. The Project Team developed and agreed to a restrictive financial plan at the outset, and proceeded to deliver full performance on time and under cost estimate. This establishes the Mariner Venus/Mercury 1973 Project not only as a distinguished member of the Mariner, and indeed the entire NASA family of projects, but as a model of cost-effectiveness as well.

"Mariner 10 is nominally 'completed' and has met in full all the objectives that were stated in advance. It is now continuing on an extended mission which, hopefully, will give NASA, the scientific community, and the taxpayers the bonus of a second mission to Mercury on the same flight. All of us in NASA take great pride in the achievements of the Mariner 10 team–scientific, technical, and managerial–and offer them our enthusiastic congratulations."

NASA Distinguished Service Medal

Jet Propulsion Laboratory

Walker E. Giberson

NASA Outstanding Leadership Medal

Jet Propulsion Laboratory

John R. Casani

NASA Distinguished Public Service Medals

The Boeing Aerospace Company

Edwin G. Czarnecki

California Institute of Technology

Bruce C. Murray

NASA Exceptional Scientific Achievement Medals

Massachusetts Institute of Technology

Herbert S. Bridge

Jet Propulsion Laboratory

Victor C. Clarke, Jr.
James A. Dunne

University of Chicago

Enrico Fermi Institute

John A. Simpson

NASA Exceptional Service Medals

Jet Propulsion Laboratory

Lida M. Bates
Lyle V. Burden
Elliott Cutting
G. Edward Danielson, Jr.
Esker K. Davis
Richard L. Foster
Daryal T. Gant
Harold J. Gordon
Adrian J. Hooke
William R. Howard (Deceased)
Edward H. Kopf, Jr.
William I. Purdy, Jr.
Norri Sirri
F. Louis Sola
Anthony J. Spear
Gael F. Squibb
Francis M. Sturms, Jr.
Fred Vescelus
Peter B. Whitehead
James N. Wilson

NASA Public Service Awards

The Boeing Aerospace Company

Richard A. Axell
William E. Bramel
Haim Kennet
Bernard M. Lehv
George B. Rickey

Planning Research Corporation

Kunihei Kawasaki

NASA Group Achievement Awards

Flight Project Representative Team
(Award acepted by Allen P. Bowman)

Jet Propulsion Laboratory

Allen P. Bowman
Frank A. Goodwin
Harold J. Gordon
Eugene A. Laumann
Floyd A. Paul
William I. Purdy, Jr.
Michael J. Sander
F. Louis Sola
Anthony J. Spear
Eric E. Suggs, Jr.
Herbert G. Trostle

Flight Data Subsystem Development Team
(Award accepted by Alan Messner)

Jet Propulsion Laboratory

Frank F. Baran
James E. Blue
Gordon A. Crawford
Raymond P. Del Negro
Ralph De Santis
Harvey L. Jeane
Ronald R. Manaker
Carl F. Mazzocco
Alan Messner
Martin N. Orton
Richard Piety
Thomas Shain
John H. Shepherd
L. Richard Springer
James Stahnke
Fred A. Tomey
Ralph E. West
Peter B. Whitehead
Jervis L. Wolfe
Larry W. Wright

Motorola, Inc.

Philip Girard
William Hatcher
David Skoumal
Harry Wagner

Ground Data System Integration Team
(Award accepted by Robert G. Polansky)

Jet Propulsion Laboratory

James W. Capps
John M. Carnakis
Edward L. Dunbar, Jr.
Richard L. Foster
C. Wayne Harris
Jay A. Holladay
David B. Lame
H. Richard Malm
Robert G. Polansky
Thomas M. Taylor

Philco-Ford Corp.

Nick Fanelli

Mission Control and Computing Center
(Award accepted by Michael J. Sander)

The Boeing Aerospace Company

D. M. Sargent

Jet Propulsion Laboratory

Wailen E. Bennet
Richard L. Foster
Ralph P. Hurt
David B. Lame
Gary D. Metts
Rolf H. Niemeyer
George M. Reed
Michael J. Sander
William H. Stapper
Michael R. Warner

Philco-Ford Corp.

Bruce H. Walton
Eugene G. Herrington
Edward R. Kelly
Allan L. Sacks

Planning Research Corp.

Kunihei Kawasaki

Mission Sequence Working Group
(Award accepted by Rodney Zieger)

Jet Propulsion Laboratory

G. Edward Danielson, Jr.
Adrian J. Hooke
Kenneth P. Klaasen
Lawrence Koga
Sergio X. Madrigal
Donna L. Shirley
Ronald C. Spriestersbach
Gael F. Squibb
Kennis Stowers
Robert I. Toombs
William A. Webb
Clayne M. Yeates
Steven J. Zawacki

Philco-Ford Corp.

Roy E. Bates
Patricia M. Kirkish

The Boeing Aerospace Company

Michael R. Cramer
George M. Elliott
Merlyn J. Flakus

Bernard R. Migas
Dudley A. Vines
Rod Zieger

Navigation Development and Operations Team
(Award accepted by Jeremy B. Jones)

Jet Propulsion Laboratory

Marvin H. Bantell, Jr.
Raymond A. Becker
Carl S. Christensen
Leonard Dicken
Vincent L. Evanchuk
Harold J. Gordon
Jeremy B. Jones
Roger E. Koch
C. Jeffrey Leising
Edward L. McKinley
Richard V. Morris
V. John Ondrasik
Gerald E. Pease
Stephen J. Reinbold
Andrey Sergeyevsky
Gary L. Sievers

The Boeing Aerospace Company

Jarrett H. Thomas

Roll Axis Anomaly/Solar Sailing Team
(Award accepted by Walter F. Havens)

Jet Propulsion Laboratory

Teofile A. Almaguer, Jr.
Alan T. Campbell
A. Earl Cherniack
Vincent L. Evanchuk
Patrick J. Hand
Walter F. Havens
John M. Kent
Edward H. Kopf, Jr.
William I. Purdy, Jr.
Jack W. Rhoads
Lawrence L. Schumacher
Robert L. Shrake
Stephen Z. Szirmay
Jaiyun M. Yuh

The Boeing Aerospace Company

John R. Barton
Julius D. Budos
Tord Dannevig
C. Thomas Golden
Jerome H. Hardman
Robert P. Lang
David H. Merchant
Bernard R. Migas
Paul H. Stern

Television Subsystem Development Team
(Award accepted by David Norris)

Jet Propulsion Laboratory

Lloyd A. Adams
G. Edward Danielson, Jr.
Harry T. Enmark
Mark Herring
Kenneth C. La Bau
Clayton C. La Baw
Leonard Larks
David Norris
Gerald M. Smith
Daniel L. Smyth
Fred Vescelus
Joachim G. Voeltz

Electro-Optical Systems

William Cunningham
Nicolaas M. Emmer

Work Unit Management Team
(Award accepted by Teofile A. Almaguer, Jr.)

Jet Propulsion Laboratory

Jerome E. Abraham
Teofile A. Almaguer, Jr.
Philip M. Barnett
Raymond A. Becker
C. Glen Bullock
Frederick R. Chamberlain
G. Wade Earle
Vincent L. Evanchuk
Arthur O. Franzon
Robert E. Freeland
H. Kent Frewing
Edward G. Gregory
Donald E. Hayes
Donald D. Howard
Herman L. Johnson
L. Earl Jones
Edward E. Kellum
Dan B. Kubly
Donald D. Lord
Floyd A. Paul
James A. Roberts
Charles H. Savage
L. Tom Shaw
Charles A. Smith
Stephen G. Sollock
Alvin B. Sorkin
James H. Stevens
William H. Tyler
Ronald J. Zenone

System Contract Procurement Team
(Award accepted by John Heie)

Jet Propulsion Laboratory

Daryal F. Gant
John Heie

Eugene C. Reiz
Donald E. Weckerle

Jet Propulsion Laboratory
(Award accepted by William H. Pickering)

Leticia Eckerle
Bruce M. Hayes
John C. Hewitt
Sharon D. Jones
Harold J. Wheelock

Mariner 10 Headquarters Staff Support Group
(Award accepted by Stephen E. Dwornik)

Maurice E. Binkley
Stephen E. Dwornik
Nicholas W. Panagakos
Robert F. Schmidt
Guenter K. Strobel

Spacecraft Flight Operations and Mission Control Teams
(Award accepted by Merlyn J. Flakus)

Jet Propulsion Laboratory

Jerome E. Abraham
Teofile A. Almaguer, Jr.
Rebecca L. Arenas
Ronald S. Banes
Dallas F. Beauchamp
Raymond A. Becker
Albert G. Brejcha
Phillip E. Brisendine
C. Glen Bullock
Ralph De Santis
Larry N. Dumas
James A. Dunne
John E. Earnest, Jr.
Robert E. Edelson
Vincent L. Evanchuk
Robert A. Exler
H. Kent Frewing
Walter F. Havens
Mark Herring
Adrian J. Hooke
Harvey H. Horiuchi
Oscar L. Irvin
William N. Jensen
John M. Kent
Edward H. Kopf, Jr.
Clayton C. La Baw
Paul Lecoq
C. Jeffrey Leising
Donald D. Lord
Dan S. MacGregor
Sergio X. Madrigal
John C. McKinney
Alan Messner
Hiroshi Ohtakay
Richard B. Postal
William I. Purdy, Jr.
Jack W. Rhoads
Eddie Royal
Lawrence L. Schumacher
Robert A. Shepard
Charles A. Smith
Richard L. Smith
Daniel L. Smyth
F. Louis Sola
Anthony Joseph Spear
Ronald C. Spriestersbach
Gael F. Squibb
Garvin T. Starks
Kennis Stowers
Eric E. Suggs, Jr.
David H. Swenson
Fred A. Tomey
William H. Tyler
Peter B. Whitehead
Vincent A. Wirth, Jr.
Regina F. Wong
Clayne M. Yeates
Jaiyun M. Yuh

The Boeing Aerospace Company

Ross E. Barta
John R. Barton
John H. Bruns
Julius D. Budos
Theodore C. Clarke
Richard T. Cowley
Emery J. Durand
Michael D. Ebben
Merlyn J. Flakus
Malcolm D. Gray
Jerome M. Hardman
Lawrence A. Hughes
William F. Just
James Leisenring
Robert K. MacGregor
Boyd D. Madsen
F. Alfred Matzke
Bernard R. Migas
Ken Nakagawa
Harold L. Nordwall
Donald M. Sargent
James F. Schmidling
Larry D. Shirk
Charles H. Terwilliger
Jarrett H. Thomas
James R. Williams
Ronald C. Zentner
Victor S. ZumBrunnen

Philco-Ford Corp.

Conni J. Berry

Electro-Optical Systems

William Cunningham

Boeing Aerospace Management Team
(Award accepted by O. C. Boileau, President, The Boeing Aerospace Company)

Data Records Group
(Award accepted by John R. Tupman)

Alpha Services

Edward J. Philips

Jet Propulsion Laboratory

Roger W. Burt
Richard L. Foster
Raul D. Rey
Concomly A. Seafeldt
John R. Tupman

Philco-Ford Corp.

Ray Caswell
Dale Christiansen
Earl T. Lobdell
Michael A. Orr
Allan L. Sacks
Donna Stapper

Planning Research Corp.

James P. Dunphy
Kunihei Kawasaki

The Boeing Aerospace Company

Roger A. Vail

V.I.P. Engineering Co.

Harold Hsu

Science Instrument Development Team
(Award accepted by David H. Swenson)

Goddard Space Flight Center

Kenneth Behannon

Jet Propulsion Laboratory

David H. Swenson
Clayne M. Yeates

Kitt Peak National Observatory

Samuel C. Clapp

Massachusetts Institute of Technology

Robert Butler

Santa Barbara Research Center

Jack Engel

The Boeing Aerospace Company

John H. Bruns
Theodore C. Clarke
F. Alfred Matzke
Ken Nakagawa

University of Chicago

James E. Lamport

Television Science Team
(Award accepted by Bruce C. Murray)

Ames Research Center

Donald E. Gault

California Institute of Technology

James L. Anderson
Bruce C. Murray

Hampshire College

Brian T. O'Leary

Jet Propulsion Laboratory

Wailen E. Bennett
Virgil B. Combs
G. Edward Danielson, Jr.
Ralph A. Johansen
Kenneth P. Klaasen
David Lame
Jean J. Lorre
Donald J. Lynn
John R. Schoeni
James M. Soha
Robert I. Toombs

Kitt Peak National Observatory

Michael J. S. Belton

Philco-Ford Corp.

David L. Atwood
Michael Morrill
Norma J. Stetzel

Planning Research Corp.

Joanne Currie

The Rand Corporation

Merton E. Davies

University of Arizona

Gerard P. Kuiper (deceased)
Robert Strom

University of London Observatory

John Guest

University of Pittsburgh

Bruce W. Hapke

University of Wisconsin

Robert Krauss
Verner E. Suomi

U.S. Geological Survey

Newell J. Trask

Spacecraft System Design Team
(Award accepted by James M. Ellis)

The Boeing Aerospace Company

William E. Bramel
Dwayne E. Broderson
Tord Dannevig
Gordon N. Davison
David R. Douglass
James M. Ellis
Merlyn J. Flakus
C. Thomas Golden
Ivan W. Hudgins
Bernard M. Lehv
Charles W. Luke
George B. Rickey
Edwin E. Spear
Douglas B. Stoddard
Charles H. Terwilliger

Temperature Control Design Team
(Award accepted by Raymond A. Becker)

Jet Propulsion Laboratory

Raymond A. Becker

The Boeing Aerospace Company

Robert K. MacGregor
Harold L. Nordwall

Boeing Cognizant Work Unit Engineers
(Award accepted by Paul H. Stern)

The Boeing Aerospace Company

John E. Anderson
Ole A. Bakken
George C. Bentley
Freddie G. Boyd
Steve S. Campbell
Leonard Cancler
Edward B. DeGroot
David A. Dougherty
David R. Douglass
James M. Ellis
Herschel F. Eppenstein
Robert L. Farmer
Donald C. Flint
C. Thomas Golden
James P. Grady
Jack A. Grimmett
John W. Griswold
Jack W. Hakala
Roy E. Juberg
Peter V. Jude
Walter M. Keenan
Earl D. Kuhl
Morton Kushner
James A. Lackey
Robert G. Lane
Bernard M. Lehv
Patrick S. Lettenmaier
Gordon P. Lowe
Donald K. MacWhirter
Earl L. McCabe
Herbert M. McDaniel
D. Paul Meyer
Donald A. Miller
Virgil L. Minter
Warren I. Mitchell
Calvin P. Morgan
Harold L. Nordwall
Morton A. Palmer
John L. Pertesis
Lawrence C. Phelps
Francis B. Robins
Perry H. Scarlatos
Richard S. Seymour
Robert R. Shamp
Larry D. Shirk
Alan T. Simmons
Julius Skolnick
John R. Steding
Paul H. Stern
Paul L. Szyperski
George Trusk
Richard D. White
Patrick F. Wilson

Suggestions for Further Reading

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